THESIS

HYDROLOGIC SOIL STUDY OF AN ALPINE WATERSHED

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION

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BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

HYDROLOGIC SOIL STUDY OF AN ALPINE WATERSHED

A 2.3 Km^2 (0.89 sq. mi.) alpine watershed in the Colorado Front Range is partitioned into 13 hydrologic units. This partitioning is based on generic soil type, landforms, steepness of slope, and aspect. Most of the variation in hydrologic properties is reflected in the delineation of the major soil types.

Water storage in the top 1 m of soil is the major soil hydrologic property considered. Strip terraces, alluvial terraces and the concave central area are the zones with the highest water storage capacity in the watershed (average of 44 cm/m depth). The total water storage capacity of the watershed to a depth of 1 m was calculated as 6,401 x 10^2 m^3 (518 ac-ft).

Total water storage capacity in the top 1 m is inversely related to landform slope: considering all soils, the correlation coefficient is 0.84; for the podzols, 0.91. A coefficient of correlation of 0.89 exists between bulk density and detention storage capacity.

Hydraulic conductivity of selected soils ranges, in the upper horizons, from 67 cm/hr in podzol and alpine meadow soils to 16 cm/hr in lithosols and alpine turf soils. Hydraulic conductivity of all four soils decreases to 2 to 3 cm/hr at 50 to 100 cm depth.

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INTRODUCTION

The importance of water from alpine and subalpine watersheds has long been recognized. The possibility of water yield management will, in the future, require basic information on the relationships between the physical characteristics and the hydrologic behavior of these watersheds.

The present research was undertaken in order to obtain part of this information. The objective was to evolve a rational partitioning of a small upland watershed called "Upper Little Beaver Creek" into hydrologic units, based primarily on variations in hydrologic soil characteristics.

In order to accomplish this objective, the following steps were necessary:

1. Determine selected physical properties of the watershed.
2. Determine certain hydrologic properties of the soils of the watershed.
3. Relate hydrologic soil properties to the physical characteristics of the watershed.
4. Partition the watershed into Hydrologic Units, using the relationships developed.

The area of study is located at an average elevation of 3,338 m on the alpine and subalpine area of the eastern slope of the Colorado Rocky Mountains (Fig. 1). The watershed is part of the Little South Fork subwatershed of the Cache la Poudre River. It has an area of 2.309 Km^2 (0.89 sq. mi.).

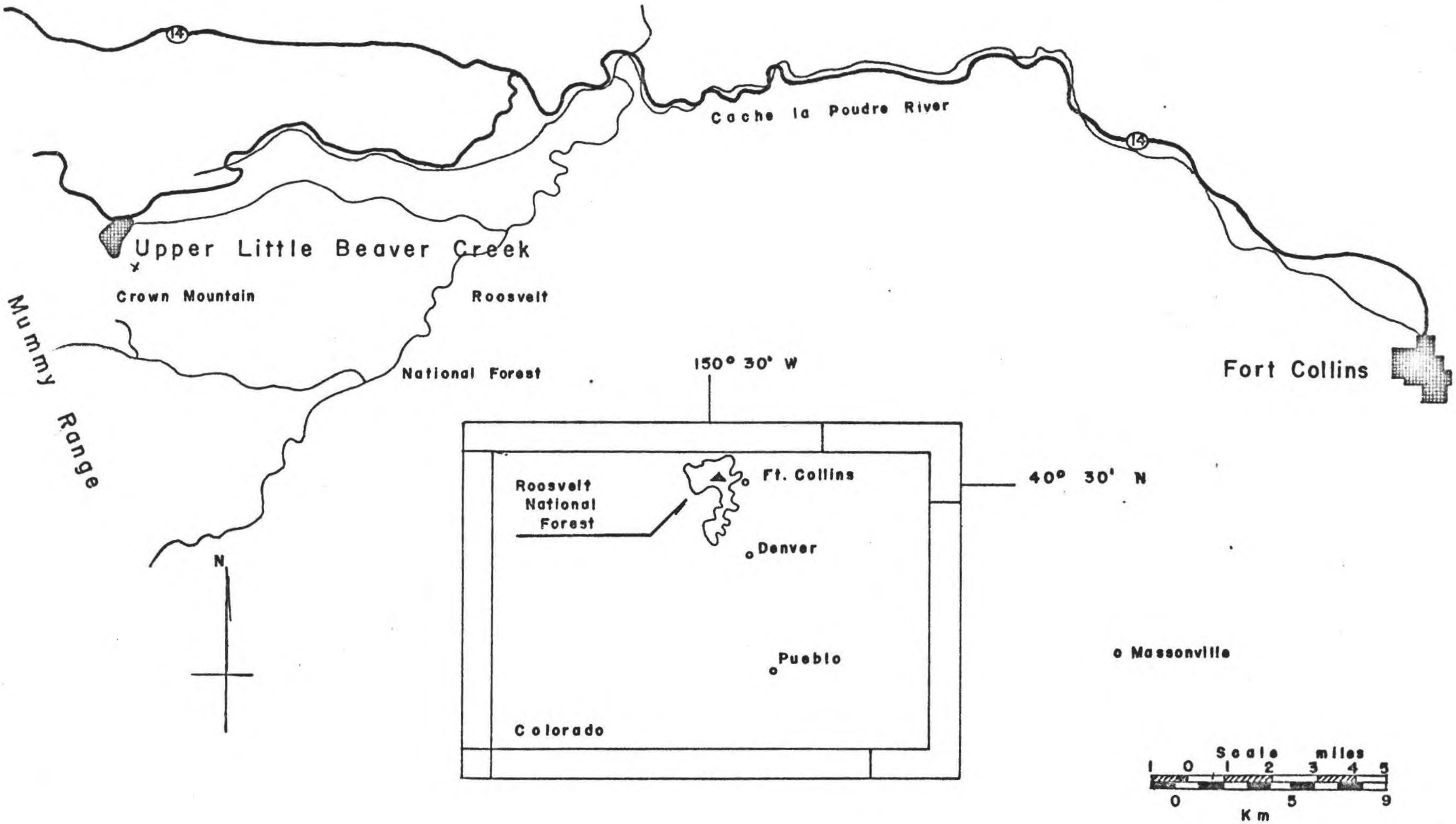

Fig. I Location of the Upper Little Beaver Creek watershed.

Chapter II

REVIEW OF LITERATURE

<u>Soils: their effect on watershed storage</u>:

The watershed is the total area above a given point on a stream that contributes water to the flow at that point (Soil, Yearbook of Agriculture, 1957).

A watershed has three dimensions: length, width and depth. The watershed works in this sense as a natural reservoir, receiving water as precipitation and discharging it as evapotranspiration, as surface runoff and as ground water storage (U. S. Forest Service Handbook 2518, 1959).

Water is stored on the surface in small depressions, in leaves, humus, ponds, and lakes or in the form of snow.

Below the surface, it may be retained in the aeration zone and in the saturation zone as ground water (Work, 1955). In the analysis of basin-water balance computations, the soil mantle is important as a storage reservoir for the infiltrating water upon which plant growth normally draws for the transpiration process. It also represents a part of the ground water zone which induces a time delay of runoff from water excesses (U. S. Army, Corps of Engineers, 1956) thus working as an important flood control factor (Linsley, et al., 1958).

The water storage capacity is affected by diverse factors. According to the U. S. Bureau of Reclamation Manual (1951), they are: The amount and distribution of precipitation and surface flow, the type of soil, the topography of the land, the extent of intake and catchment areas, the amount and type of vegetation cover, the season of the year, the previous condition of saturation, the depth to the water table and the permeability of the regolith.

Soils in high mountain watersheds are only a thin surface layer on the regolith but they control the rate and the amount of water that moves into it (Retzer, 1962).

The effect of the soils on the hydrologic behavior of the watershed has been generally studied by direct and indirect methods. The latter treats the watershed as a "black box" and considers only the input as precipitation and the output as streamflow, evapotranspiration or change in storage. After analysis of this data, it is then possible to evaluate the effect of the soils on the response of the watershed. The direct approach is to study the hydrologic characteristics of the soils of the watershed and to take direct measurements of their effect on the hydrologic behavior (Chow, 1964).

A watershed, even though small, usually includes a large number of soil types with great variations in their ability to store and transmit water (U. S. Forest Service Handbook 2518, 1959).

In order to study these variations, it is necessary to group the zones of the watershed according to their hydrologic soil characteristics. The zones thus classified are called "Hydrologic Soil-Units (Soil Conservation Service National Engineering Handbook, 1954).

Physical characteristics of the soils as related to their hydrological behavior

Leven and Williams (1967) and Holton, et al., (1967) described the physical properties of the soil that are used in the calculation of their hydrologic characteristics. They considered texture, structure, bulk density, porosity, specific gravity, stoniness, horizon depth and total depth to be the most important factors involved.

A brief discussion of how these factors are related to the water storage capacity and water movement in the soil follows.

Texture

The following general conclusions concerning soil-water relationships can be made from the standpoint of texture classes (Fisher, 1966). These relationships do not take into account the soil structure.

Coarse-textured soils generally have rapid infiltration, low water-holding capacity, small amounts of water available for plant growth and low susceptibility to compaction. They are usually well drained and porous and have rapid subsurface yield.

Medium-textured soils have moderately rapid infiltration and percolation properties, are moderately well drained, have moderate water holding capacity, subsurface water yield, surface runoff and water holding capacity.

Fine-textured soils have moderate to slow infiltration rates, slow percolation rates, high to very high water holding capacity, high available moisture for plant growth, sustained subsurface yield and rapid surface runoff.

Structure

Soil structure is related principally to infiltration and percolation rates and to water storage capacity. Lutz and Chandler (1946) and Chow (1967) explained that bulk density and pore size distribution are indirect measurements of the soil structure. Pore size distribution will determine the water storage capacity of soils. Holton, et al., (1967) noted that this effect is particularly evident at lower water tension and recommended that measurements of moisture tension at 1/3 and 1/10 atmospheres be made with undisturbed soil samples.

It is also recommended that the measurement of infiltration rates (due to their close correlation with structure) be made using non-disturbed core samples (Amer. Soc. of Agron., 1967).

Depth

Soil depth generally considers both effective depth and total depth. Effective depth is the depth to which roots extend in the soil while total depth is the depth to bedrock. According to Rothacher, et al., (1967) while soil may be considered shallow from a pedological point of view, hydrologically this so-called shallow "soil" may be classified as very deep if it overlays fractured bedrock where a potentially high storage capacity exists. This consideration should not be neglected, especially in mountain watersheds (Frank, 1963; Newhall, et al., 1965).

Holton, et al., (1967) defined the soil depth in a different way. Soil depth was defined as the depth above the impeding stratum or horizon in which the hydraulic gradient is essentially equal to unity. This strata is determined by bulk density, structure and percolation measurement. Based on the above, it was stated:

> Accepting that the major zone of agronomic and hydrologic activity lies above some depth which controls profile drainage, we can compute finite volume associated with the various moisture classes for many soils.

Bulk Density

Soil bulk density is the ratio of the mass to the bulk of macroscopic volume of soil particles plus pore spaces in a sample. Bulk density is generally expressed in g/cm^3 or $lbs./ft.^3$ It is used in the calculation of porosity (knowing the particle density of the soil) and in the conversion of moisture percentage on a weight basis to a volume basis (Millar, et al., 1965). Gessel and Cole (1958) indicated that bulk density values are directly related to water movement in the soil. They explained that at 1.7 g/cm^3 the percolation rate would be so low that drainage difficulties would be anticipated. Millar, et al., (1966) explained that the bulk density of fine-textured surface soils is usually in the range of 1.0 to $1.3/cm^3$ and in coarse-textured surface soils it is usually in the range of 1.3 to 1.8 g/cm^3.

Stoniness

Stoniness is usually expressed as the percent of the volume or area occupied by rocks or stones with a diameter bigger than 2 mm.

Values of stoniness are used to correct the values of water storage in the soil (Rothacher, et al., 1967).

Lutz and Chandler (1946), Tyurin (1959), Chow (1952) and others mention the importance and effects of rocks and stones in the soil-water relations. The U. S. Forest Service Handbook 2559.2 (1966) discusses a number of properties of stony soils: Stones are good conductors of heat, and as a result, stony soils are warmer and drier than soils without stones. Stones tend to make heavy dense soils more permeable to water and air. Stones increase infiltration since channels and passage ways around stones are created due to the differences in the coefficient of expansion of stone and soil. If scattered over the surface, they act as a mulch making more moisture available to plants; stones may also allow a greater interchange of air and may increase the water loss due to evaporation. A stony soil will be moist to a greater depth than one of a similar texture without stones since the available moisture will be concentrated in the soil due to the impermeability of the stones.

Freezing

Water movement and storage in the soil are affected by the soil temperature.

According to Storey (1955) soil freezing is an important hydrologic factor in the parts of the United States where low winter temperatures prevail and the snow cover is light. Four characteristics of frozen soils affect the soil water storage capacity: 1) structure, 2) depth of penetration of soil frost, 3) persistence of soil frost and 4) extent of soil frost. He stated that as little as one inch of frozen soil may prevent infiltration due to its relative impermeability. Some of the effects of soil freezing on water yield have been studied by Stoeckler and Wetzman (1960) and Mace (1968).

Stoeckler and Wetzman compared frozen sandy soils and frozen silt loams and found that infiltration rates are substantially higher in the former during the melting period. They associated this effect with the type of drainage. In poorly drained areas frost penetrates deeper.

Mace, in the same type of study in the White Mountains of Arizona, found that the type of frost, concrete or granular, influenced the disposition of snow melt water in the soil. He found that concrete frost in grassland areas appeared to decrease soil moisture and increase surface runoff and that in the later stages of the snow melt period when the soil was rapidly thawing the same type of frost increased the soil moisture, reduced runoff and reduced bulk density. The granular type of frost occurring under timber was found to decrease surface runoff and increase the soil moisture recharge.

Porosity

Amer. Soc. of Agron. (1965) defined porosity as the fraction of the soil volume not occupied by soil particles. It is expressed as the percentage by volume of a dry soil occupied by pore space.

The total porosity determines the total water holding capacity of the soils when fully saturated (Gessel and Cole, 1958).

The pore size distribution greatly influences the rate of water movement through soils. In general, without considering the effect of soil structure, large pore space results in low water holding capacity. Rapid percolation will occur with relatively little water being held by forces of surface tension. Small pore space on the contrary, will result in greater water holding capacity and will allow less water to percolate (U. S. Forest Service Handbook 2559-2, 1959).

The practical application of porosity consideration is in the calculation of total water storage capacity, detention capacity, retention capacity and water available for plants based on values of soil moisture retention at various levels.

Hydrologic soil characteristics

Water intake by soils

Rate of intake of water by soils refers to the movement of water downward into the soil surface per unit area per unit time (Amer. Soc. of Agron., 1965). It is also called infiltration rate.

The readiness of a soil to absorb water is reflected in the hydrologic behavior of watersheds. According to Meinzer (1942), it influences directly and indirectly the occurrence of floods, the levels of the groundwater table, the discharge from springs, the degree of turbidity of the river water, and the possibilities of plant growth.

Infiltration rate cannot be separated from percolation rate when measuring its effect on all the above. Neither can it be separated from the factors which will in turn influence it - rainfall, soils, vegetation, temperature and slope (U. S. Forest Service Handbook 2518, 1959). The primary value of the infiltration rate as a hydrologic soil factor is that it determines the time at which runoff will start as well as the amount of water intake (Meinzer, 1942).

Application of this factor has been made by the U. S. Soil Conservation Service (1964) as a hydrologic parameter to indicate the runoff potential of various soils in order to classify them into hydrologic soil groups.

To allow for the effect of percolation on infiltration, they considered only the minimum rate of infiltration obtained from a bare soil after prolonged wetting.

Values obtained from hydrograph analysis were related to hydrologic soil groups, to permeability of the subsoil, influence of slope, difference in exposure, size of the watersheds and to soil properties. It was concluded that none of the vegetation or land capability classes in the analysis showed any influence upon the plotted infiltration rates and that the water intake seemed to be influenced more by factors which reflected hydrologic soil properties. One of the most important factors was the availability of storage space in the soil which lengthens the time required to attain the minimum infiltration rate.

Hydraulic conductivity of soils

The rate of movement of water through saturated or unsaturated soil is of considerable importance in the hydrologic behavior of the watershed. It controls the entry of water into soil (infiltration), the flow of water to drains and wells (subsurface flow), the evaporation of water from the surface of soils, and the water available for plants and thus affects evapotranspiration (Amer. Soc. of Agron., 1965). It was stated in the same reference that saturated samples are commonly used to evaluate the effect of the rate of water movement. This is because hydraulic conductivity of saturated soils is a constant which relates, for a given soil, the rate of water transport in that soil to the hydraulic gradient or driving force causing the water to move. The evaluation of this constant can be made as a measurement of the downward movement of water through soils (percolation) or of the lateral movement of water along the horizon and can be used as a hydrologic parameter (Soil Conservation Service, National Engineering Handbook, 1964).

Hydraulic conductivity has the dimensions of velocity L/T and it appears as the proportionality factor in the Darcy Law (Richards, et al., 1954). Hydraulic conductivity is commonly referred to as percolation rate or transmission rate.

Storage capacity of the soils

The amount of water which a soil can store has been frequently studied primarily in relation to the water available for plants.

Maximum water storage capacity, field capacity and wilting point are the common names which designate respectively 1) the amount of water present when all the pores in the soil are saturated, 2) the maximum amount of water which a soil will hold with unrestricted drainage and 3) the minimum point of moisture availability below which plants permanently wilt. All three are usually expressed in percentage of weight or volume. Forces holding the water at field capacity are considered equal to 0.33 bars and at wilting point, 15 bars (Amer. Soc. of Agron., 1965).

The water in the soil has been classified as gravitational, capillary, and hygroscopic (Baver, 1956). Gravitational water is that which moves through the large pores and voids of the soil due to the force of gravity. It represents the difference between maximum storage capacity and field capacity. As its name implies, capillary water is that retained in soil capillaries or small pores against the force of gravity. This is the water which is available for plant growth (the volume of water between field capacity and wilting point). Hygroscopic water is all the water remaining in the soil below the wilting point. Todd (1964) defined hygroscopic water as the water held between hygroscopic coefficient and zero vapor pressure. Hygroscopic coefficient is further defined as the maximum moisture which an initially dry soil will absorb in contact with an atmosphere of 50 percent relative humidity.

Fig. 2 shows the different classes and equilibrium points considered above.

In hydrology the same general classification is used but sometimes different names define the divisions as defined by Newhall (1965).

Soil Suction (Bars)

0 — Maximum water capacity

gravitational water

0.33 — Field capacity

capillary water — water available for plants

15 - - - - - - - - - - - Wilting point

Hygroscopic coefficient

Hygroscopic water

Fig. 2. Soil-water relations.

Retention and detention storage capacity are terms commonly employed. Retention capacity is equal to the water available for plants plus the hygroscopic water, detention capacity refers to the gravitational water, which moves slowly downward and out through soil and rock into springs and streams.

<u>Watershed factors related to hydrologic soil characteristics</u>:

Hydrologic soil characteristics cannot be separated in practice from the watershed factors which will affect them changing their response as storage units. However, artificial separation is necessary in order to understand how each factor participates in the hydrologic process (U. S. Forest Service Handbook 2518, 1959).

The complex interrelationships of all these factors were thoroughly discussed by Chow (1964), Linsley (1942), in the U. S. Forest Service Handbook 2518 (1959), in the Bureau of Reclamation Manual (1950) and in the Soil Conservation Service National Engineering Handbook (1954).

According to Chow (1954), a particular value can be assigned to each factor which participates in the hydrologic process in order to evaluate the entire hydrologic behavior of a watershed. One of the methods suited to this purpose is the classification of hydrologic units. This classification is made combining a specific hydrologic soil unit with a specific cover and is used as a watershed parameter.

Hydrologic soil groups and soil cover complexes

Diverse methods are described for the separation of hydrologic soil groups in the Soil Conservation Service National Engineering Handbook (1964), in the U. S. Forest Service Handbook 2518 (1959) and by Holton, et al. (1967).

The Soil Conservation Service defines four hydrologic soil groups based on their minimum rate of infiltration obtained for a bare soil after prolonged wetting, and on their relative rates of water transmission. In total, they classified more than 4,000 soils in the United States and Puerto Rico. They classified the hydrologic groups independent of their cover. Hydrologic soil cover complexes are obtained by a combination of a hydrologic soil group (soil) and a land use and treatment class (cover). Each complex has an assigned curve number (CN). The CN indicates the runoff potential of a complex during periods when the soils are not frozen.

Holton, et al., (1967) disagreed with the Soil Conservation Service classification of hydrologic soil groups by indicating that even though the soils are amenable to grouping in accordance with their water intake in a wet condition, in predicting water yields, the water intake and water storage capacities of soils must be estimated over the entire range of moisture capacities. He stated that:

> If we can accept that the major zone of agronomic activity lies above some depth which controls profile drainage, we can compute finite volumes associated with the various moisture classes for many soils. In the soils which have no evidence of an impeding strata, the depth at which seepage becomes a minimum is estimated as a depth sufficient for the hydraulic gradient to essentially equal unity.

This depth limits the zone of hydrologic activity and makes possible the computation of the hydraulic conductivity and storage capacity of the soils.

The Forest Service considers that in order to evaluate the effects of cover and soil on runoff, a study should encompass four steps:

1. Delineation in the field of the soil cover complexes with soils classified according to the Soil Conservation Service procedure. Soil characteristics used are the combinations of depth, texture and internal drainage which determine the differences in percolation storage and infiltration capacity. Covers are determined according to their range and forest hydrologic condition. Hydrologic condition is defined as "that condition of a watershed area which reflects its ability to influence runoff." In forest and woodland, consideration is given to ground cover density.

2. Field and laboratory study of soil samples to determine storage and percolation.

3. Hydrologic computation to route the water through the soil profile.

4. Hydrologic analysis to evaluate cover and soil improvement using future watershed conditions.

<u>Advances in hydrologic soil characteristics studies</u>:

General

Hydrologic soil characteristics, in general have been studied in diverse disciplines, mainly in agronomy, forestry and in agricultural and civil engineering, each with different purposes and with different methods (Holton, et al., 1967).

As a civil engineer working in hydrology, Eagleson (1967) stated that engineers in general have concentrated their efforts upon overall catchment dynamics. They have shown, with few exceptions, only secondary interest in the specific role of the soil system, and only now have they begun to evidence increasing concern with this aspect.

Bell (1967) criticized the lack of awareness among hydraulically-oriented engineers of the research on flow through porous media which has been done by agriculturally-oriented engineers.

Frank (1963), watershed management researcher, complained that the present methods of inventorying and classifying forest soils are still too heavily based upon agronomic objectives and are lacking in hydrological data.

Holton, et al., (1967) aware of these problems, considered the soils as a common denominator of the above-mentioned disciplines. He used information on physical properties of various soil types, primarily from the Soil Conservation Service, soil survey reports, state agricultural experiment station reports and publications of the Agricultural Research Service to compute soil characteristics useful in the estimation of hydrologic capacities of the soils. The Agricultural Research Service has already published data on moisture tension and percolation rates for some soil types (Holton, et al., 1968).

Upland watersheds

In upland watersheds very little has been done in studying hydrologic soil characteristics. The problem was stated by Newhall and Smith (1965)

> Many of the important ground water reservoirs of the United States and their management problems have already been described but mostly in the downstream portions of river basins. Less is known about the upstream portions - large masses of soil and rock through which ground water percolates slowly. Less studied and often less intensively managed, they are nonetheless very important as natural detention reservoirs.

This lack of hydrologic information was also stated by Fisher (1966) and Johnson, et al. (1963).

At present the hydrologic soil studies or general soil studies which take into consideration soil-water relationships in upland watersheds are mainly on experimental sites (Rothacher, et al., 1967; Retzer, 1962).

Alpine and subalpine soils of the Rocky Mountains:

General

According to Retzer (1948), the Rocky Mountains are mantled with a variety of soils ranging from very immature to very mature. They have profiles which may be stony or free of stones, shallow or exceptionally deep, porous and droughty or poorly drained. An exceptionally wide range of variation can be studied in a relatively small area. He stated that the soils of the Rocky Mountains are by no means all shallow and stony and this suggests the importance of their role in the hydrologic cycle.

Marr (1961) in his publication "Ecosystems of the East Slope of the Front Range in Colorado" dealt in detail with four climatic regions of the area: The Lower Montane, the Upper Montane, the Subalpine and the Alpine. Johnson and Cline (1965) used the same regional subdivisions as a basis for discussing the soil patterns of the mountainous areas of Colorado. They included one additional subdivision: mountain parks and meadows.

Alpine and subalpine soil characteristics

According to Johnson and Cline (1965), and Retzer (1956 and 1962), the predominant soils of the alpine zone are: alpine meadow, alpine turf, bog soils and lithosols. The major soils of the subalpine area are: brown podzolic, podzol, lithosols, brown forest, gray wooded and bog soils.

The Colorado Front Range subalpine zone according to Marr includes areas between 2,910 m (9,300 feet) and timberline. The topography of this area is usually very steep, sometimes formed by glacial activity. Vegetation is generally dense evergreen forest, spruce, fir, and limber pine. The average precipitation ranges from 625 to 750 mm (25 to 30 inches). Parent material is generally crystalline rock. Annual soil temperatures average 0 to 6 C (32 to 42 F).

The Colorado Front Range alpine zone is located generally between 3,353 and 4,267 m (11,000 and 14,000 feet). Vegetation is usually perennial grasses, sedges, shrubs and herbs. The average annual precipitation ranges from 625 to 875 mm (25 to 35 inches) the annual soil temperature averages -4 to 0 C (28 to 32 F). Advanced weathering processes occur in crystalline rocks, stony soil and rock talus.

Johnson and Cline (1965) described the principal soils of the alpine and subalpine zone as follows:

1) Alpine meadows are dark colored soils with a profile composed of A, A3, B2 irg, Cg horizons. They are located in areas that are imperfectly to poorly drained and are acid in reaction. They can grade into alpine turf, brown podzolic, or humic gley soils according to variations in drainage, elevation, timber cover or alkalinity.

2) Alpine turfs are the most extensive soils of the alpine area. They are well drained and occur on rolling to steeply sloping alpine areas. The parent material is variable. A typical profile includes A1, A3, B_2ir, C and R horizons. These soils grade with poor drainage into alpine meadows, with decreasing elevation into podzol and with increasing alkalinity into brunizen or chernozem soils.

3) Bog soils are organic soils with very poor drainage. In the alpine and grassland areas, they are associated with hydrophytic plants and contain very fine textured organic material. A typical profile shows only two horizons, A and C. These soils, with improved drainage, grade into humic gley soils.

4) Lithosols are found wherever bedrock occurs at or near the surface of the ground. They are well drained, shallow and stony soils. They develop on moderate to steeply sloping areas. A typical profile includes A1, C, and R layers. These soils grade with variation of depth, age, effective soil moisture, depth of regolith, vegetation and change in elevation into regosols, brown soils, chernozem, alpine turf and podzolic soils.

5) Podzol profiles develop extensively in the subalpine region. Slope and aspect have little influence on their distribution. They are well drained soils developed from medium to coarse-textured parent materials under conifer cover. A typical profile shows 01, 02, A2, B_2ir and C horizons. They grade into brown podzolic or alpine turf with increasing elevation.

Hydrologic characteristics of the alpine and subalpine soils

One of the few studies of alpine and subalpine soils of the Rocky Mountains in which their hydrologic properties were not neglected is that conducted by Retzer (1962) in the Fraser Alpine Area.

He explained the hydrologic function of the soils in relation to watershed response. About two-thirds of the precipitation in the area comes as snow. The snow melt hydrograph rises in mid May, peaks in June and recedes in July. The melted water during this period is almost entirely absorbed by the porous soils, thus determining the hydrologic watershed response. Due to this characteristic, Retzer called these soils "hydrologically effective."

The subalpine soils and alpine soils, according to Retzer, are slightly different in their hydrological function, both are coarse-textured and porous but in the subalpine area the soils have a higher porosity and percolation rate. In his study, measurements of moisture tensions at 1/10, 1/3 and 15 bars were made but unfortunately values on bulk density and porosity are lacking and a quantitative measurement of the storage capacity of the area is not possible.

In the alpine area the storage is mainly in the form of snow and ice, and not in the form of water in the soil. This bulk of snow or ice sometimes does not melt completely until August or September. Vegetation in the alpine area plays an important role in holding water long enough to permit its entry into the soils.

Retzer made an estimation of the properties of the soils related to water production. He found that practically all of the different soil types classified in the area evidenced high infiltration, percolation and storage capacities with the exception of the alpine rimlands in which low percolation and storage capacity is more typical. He also classified the hydrologic soil units according to the Soil Conservation Service system. All of the units were classified into the "B" group with the exception of the bog soils which were classified as "C", and rock slides, classified as "A".

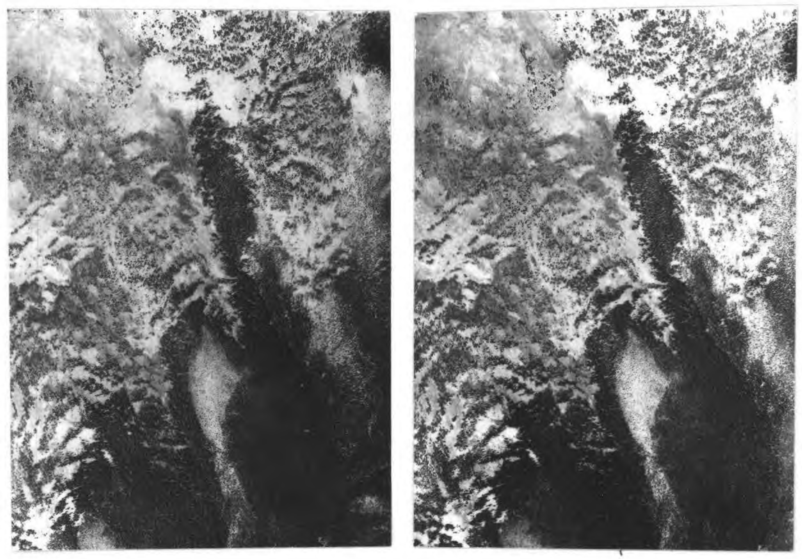

Fig. 3 Stereopair

Chapter III

ANALYSIS OF THE PHYSICAL FACTORS OF THE WATERSHED

Methods and Materials

The watershed analysis phase of this study relied heavily on existing data. A limited amount of field time (during the summer of 1968) was involved in checking and further elaboration of these data. The available information included: U. S. Geological Survey, Kinnikinnik and Comanche Peak quadrangles at a scale of 1/24,000, enlarged to a scale of 1/12,000 for the purpose of this study; aerial photos taken in 1965 for the U. S. Forest Service at a scale of 1/30,000 (Fig. 3); aerial photos taken in September 1968 at a scale of 1/20,000; maps of commercial timber from the U. S. Forest Service; previous studies by Keller (1963) on the ecological-hydrological relationships of the lower part of the watershed; reports made by Hansen (1961) on the geology of the area of study, Johnson et al., (1963) on the watershed analysis of the South Fork Basin and Murray (1968) on hydrology of the Little Beaver Creek watershed.

Additional information, obtained during 25 days of work related to the classification of the hydrologic units was included.

Description of the physical factors of the area

Physiography

The average elevation of the Upper Little Beaver Creek is 3,338 m (10.950 feet), the lowest point being at 3,049 m (10,000 feet), at which the gauging station is located. The highest point is at 3,497 m (11,462 feet), which corresponds to the top of Crown Point (Fig. 4).

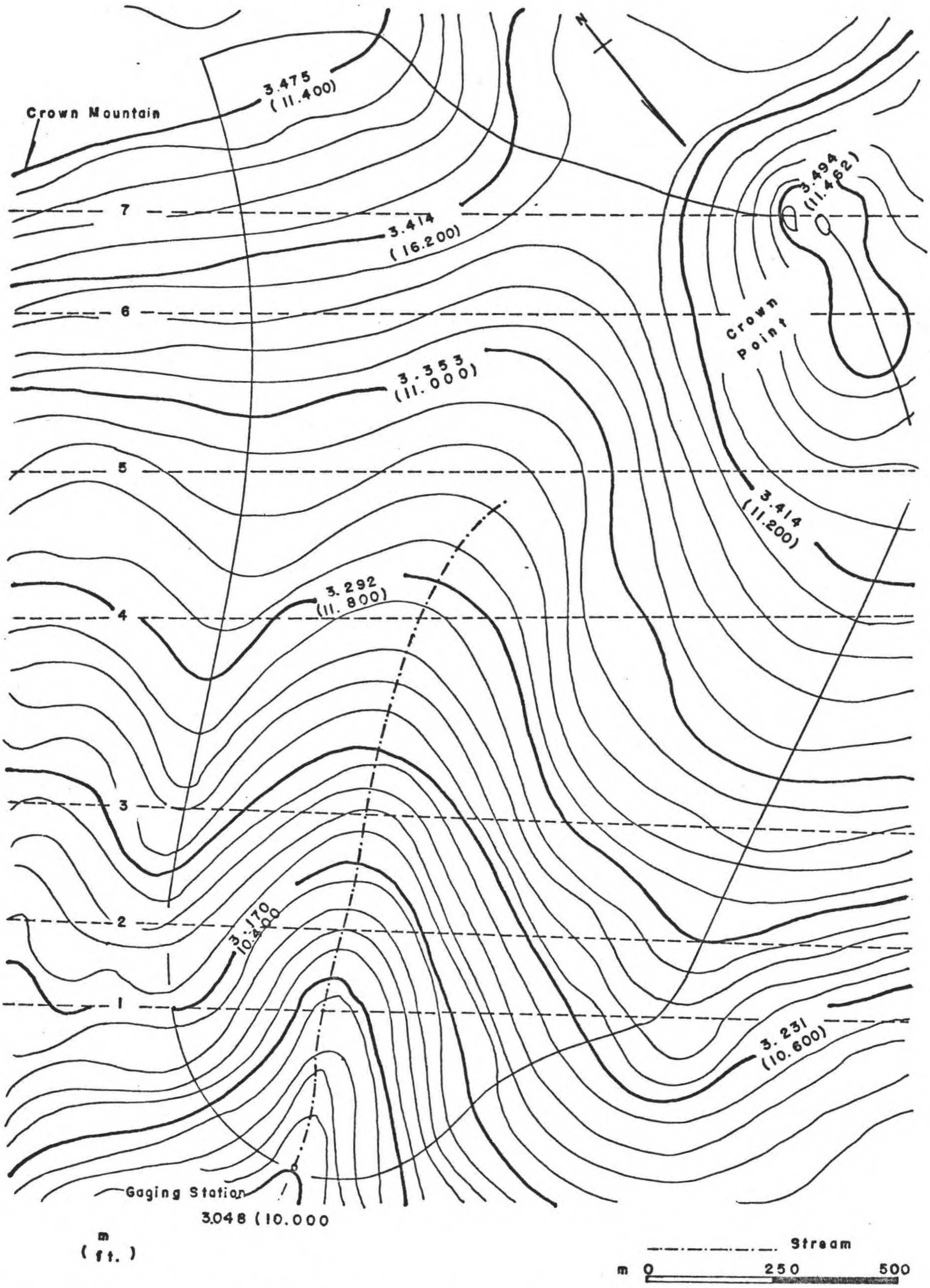

Fig. 4 Topographic map of the Upper Little Beaver Creek watershed-from U.S.G.S. maps - and cross sections location.

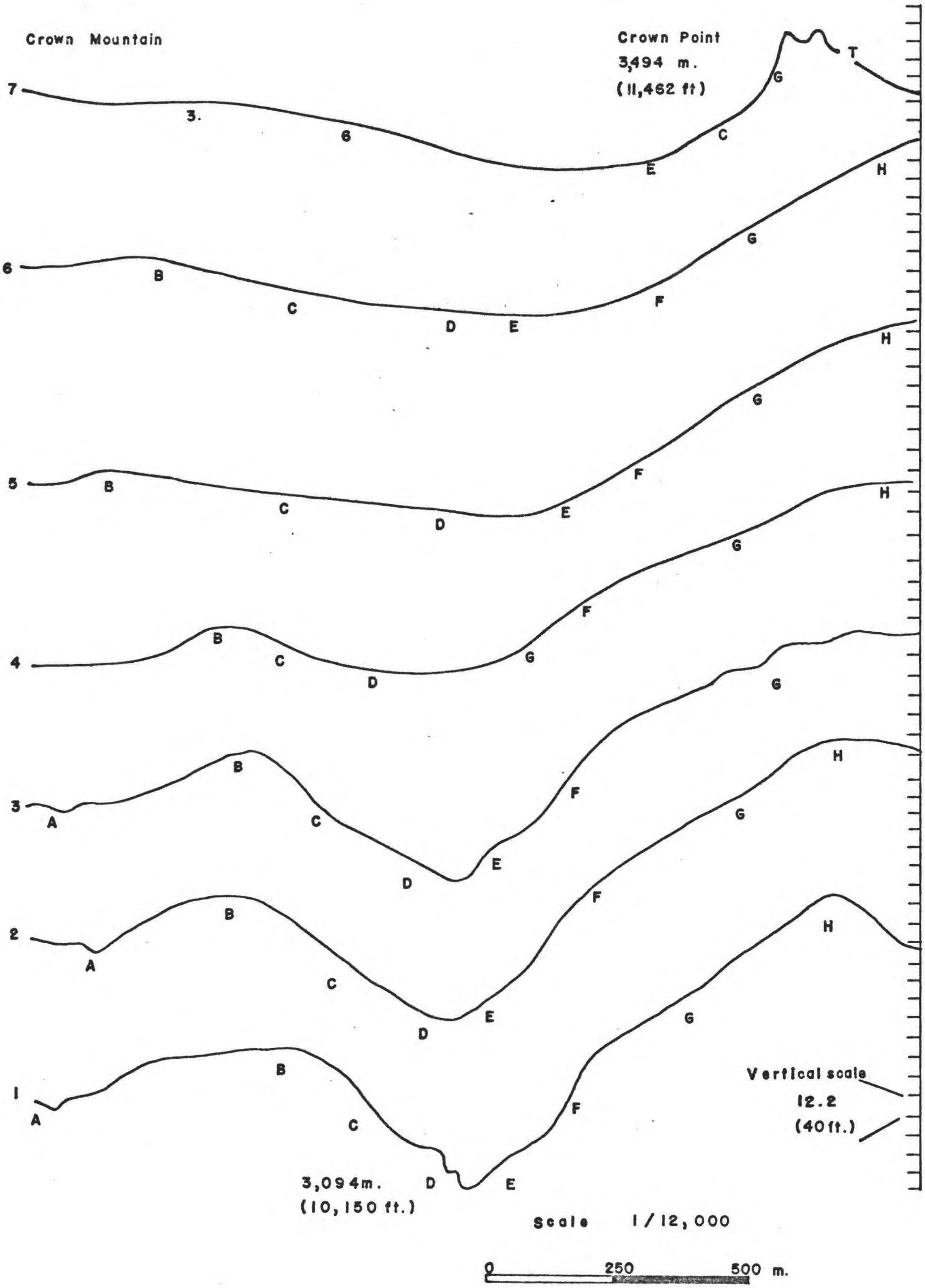

Fig.5 Cross sections 1-7 showing the variation of slopes with elevation. Letters refer to notes in the text.

The watershed covers an area of 2.309 sq. Km. (0.89 sq. mi.). In a horizontal distance of 1,300 m (4,265 feet), the difference in elevation from the lowest point to the highest one is 446 m (1,463 feet). The length of the main stream is 1,609 m (1 mile). The watershed has 56% of its area facing east, 15% north and 29% facing northeast. The watershed, according to Keller (1963), has a compactness coefficient of 1.15, a drainage density of 1.2 and an average slope of 23%.

Seven cross-sections, indicated on the topographic map (Fig. 4), are presented in Fig. 5. They show the variations on slopes with increase in elevation above the gauging station.

Cross-section No. 1 is V shaped with steep sides. It is located immediately above the gauging station. The steepest parts are the F and C zones on the east and the north-facing slopes; Zone D shows banks along the bottom of the main stream which form uneven terraces on the north-facing side. Zone G at this particular elevation of the watershed has steep slopes. In the same cross-section, Zone A represents the location of a stream south of Upper Little Beaver Creek. This stream is located at an elevation of 60.8 m (200 feet) above the gauging station. This difference in elevation is particularly important in explaining the discharge in the area of a spring which emerges in the upper part of the north-facing slope (Zone C). Cross-sections 2, 3 and 4 show the modification of the slopes from a V toward a concave shape. In cross-section 4, Zone G reveals a series of strip terraces. Cross-sections 5, 6 and 7 show the disappearance of the main stream channel as well as the appearance of rolling, smooth slopes on the northeast-facing sides of Crown Mountain. The east-facing slope increases gradually as it approaches Crown Point.

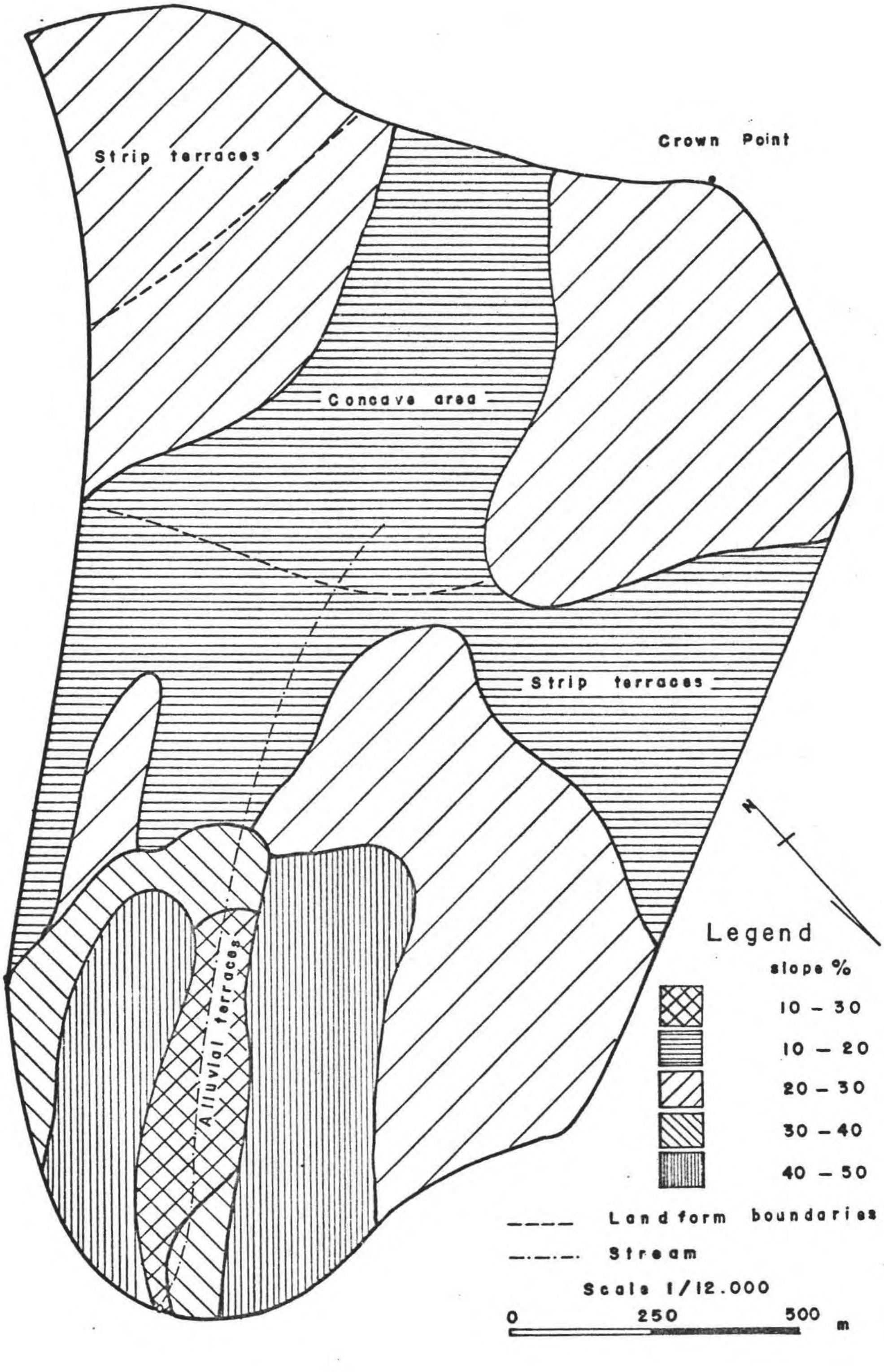

Fig. 6 Slope distribution and location of the major landforms.

The distribution of the percentage of surface area on different slopes is as follows:

Percent slope	Percent area
40 - 50%	13
30 - 40%	5
20 - 30%	46
10 - 20%	36

Climate

The climatic pattern of the general area as well as that of the Upper Little Beaver Creek has been studied by Marr (1961), Keller (1963), Ollman (1965), Judson (1965), the Colorado Game, Fish and Parks Department[1/] and Murray (1968). In 1960 a snow course was established in the area by Colorado State University and a gauging station by the U. S. Geological Survey.

The climate of the Upper Little Beaver Creek is typical of high elevations in the front range of the Colorado Rocky Mountains. The movements of the storms vary according to the season of the year (Marr, 1961), (Judson, 1965). During the winter season, storms move from the west and deposit moisture mainly on the western sides and on the high mountain passes. Frequently during the spring and occasionally in the fall, gulf air brings moisture to the east face of the Rockies. Convective thunderstorms are characteristic of the summer season. The prevailing winds are from the northwest.

No permanent climatic station has been established in the area. The only consistent records available on precipitation, air and soil temperature, relative humidity, soil moisture and wind were taken by the Colorado Game, Fish and Parks Department during the years 1961-1965.

1/ Data obtained by Al Anderson

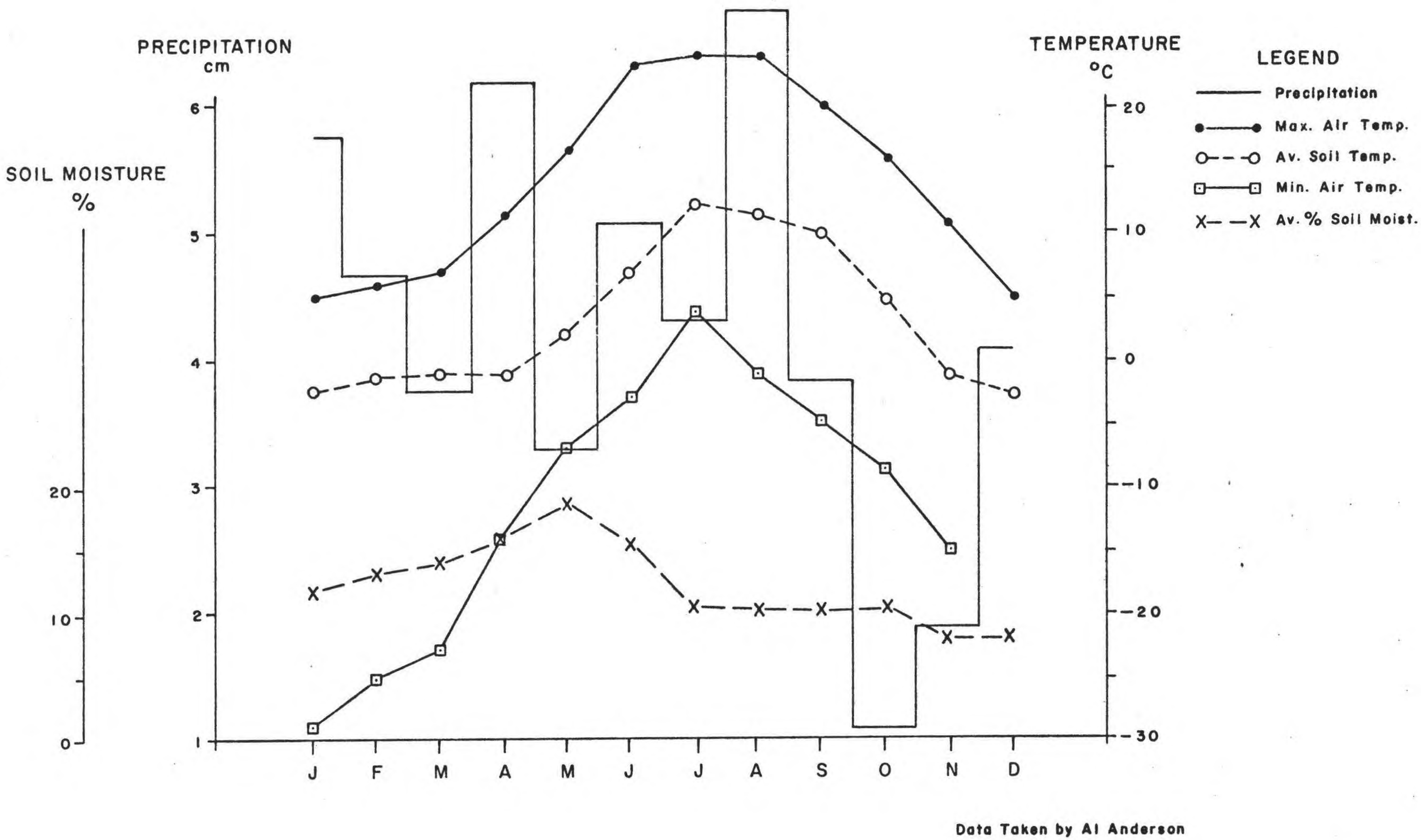

Fig. 7 Relationships among precipitation, max. and min. air temperature, soil temperature and percent of soil moisture of the Upper Little Beaver Creek watershed for an average of 3 years (1962-64)

Their station was located on the slopes of Crown Point at 3,550 m (11,320 feet). They also recorded snow accumulation which can be correlated with the Sheep Saddle Course established by Colorado State University in 1960. Fig. 7 is presented to show the relationships among the available climatic data for an average of three years (1962-1964).

Ollman (1965) made a study of summer precipitation on the Little South Fork basin which includes the Upper Little Beaver Creek. He drew three isohyetal maps showing the great variations in the summer rainfall patterns in the area.

Estimates of radiation can be obtained from Frank and Lee (1966) and crrected for altitude using the methods presented by Beker and Boyd (1953).

Field observations, available records and the topography of the area suggest that large variations in microclimate occur within short distances.

Hydrology

Murray (1968) described the general hydrologic behavior of the entire Little Beaver Creek watershed which has a total of 28.4 Km^2 (11 sq. mi.) and includes the zone of the present study. In a recession analysis he found a very steep rise followed by a long recession curve only interrupted by thunderstorm-runoff during July and August. The flow is then steady from October through May. He concluded that the winter precipitation, stored as snow pack, melts at the beginning of May with the peak of annual runoff occuring in early June.

Keller (1963) and Murray (1968) explained that the coarse porous nature of the soils of the Upper Little Beaver Creek suggested that there was very little surface runoff, and that soon after the snow melt peak the streamflow is delivered from some form of storage. Murray evaluated two parameters of the recession curve and described a third possible parameter not calculated. It appeared that there were three contributing sources of storage: snow, soil, and aquifer in a trend of exponentially decreasing rate.

A recession curve for the years 1962-1964 for the Upper Little Beaver Creek (Fig. 8) confirms Murray's conclusions. The hydrograph shows a very steep rise beginning at the end of April with the highest peak occurring in the middle of June. This is followed by a long recession curve. It is clearly visualized that there are three different slopes on the recession curve. The first one from June 17 to August 10, the second one from August 10 to February 25 and the third one after February 25. The amount of water released from June 17 to February 25 is equal to 2.565 m^3 (172.0 acre-feet).

During the field survey, several springs were recorded on a map (Fig. 9). These springs were found on the east- and north-facing slopes. The springs located on the east-facing slopes appear to originate from percolation of water from strip terraces located near the ridges. These terraces are characterized by the presence of bog soils and accumulation of water (Fig. 31). The above mentioned springs emerge at the middle of the slope and join the main stream, while others appear and disappear in a short distance. Still others emerge on the Bennet Creek watershed located north of the area under study. Apparently in this area the bedrock is highly fractured allowing water to move freely at some distance below the surface and to pass from one watershed to another.

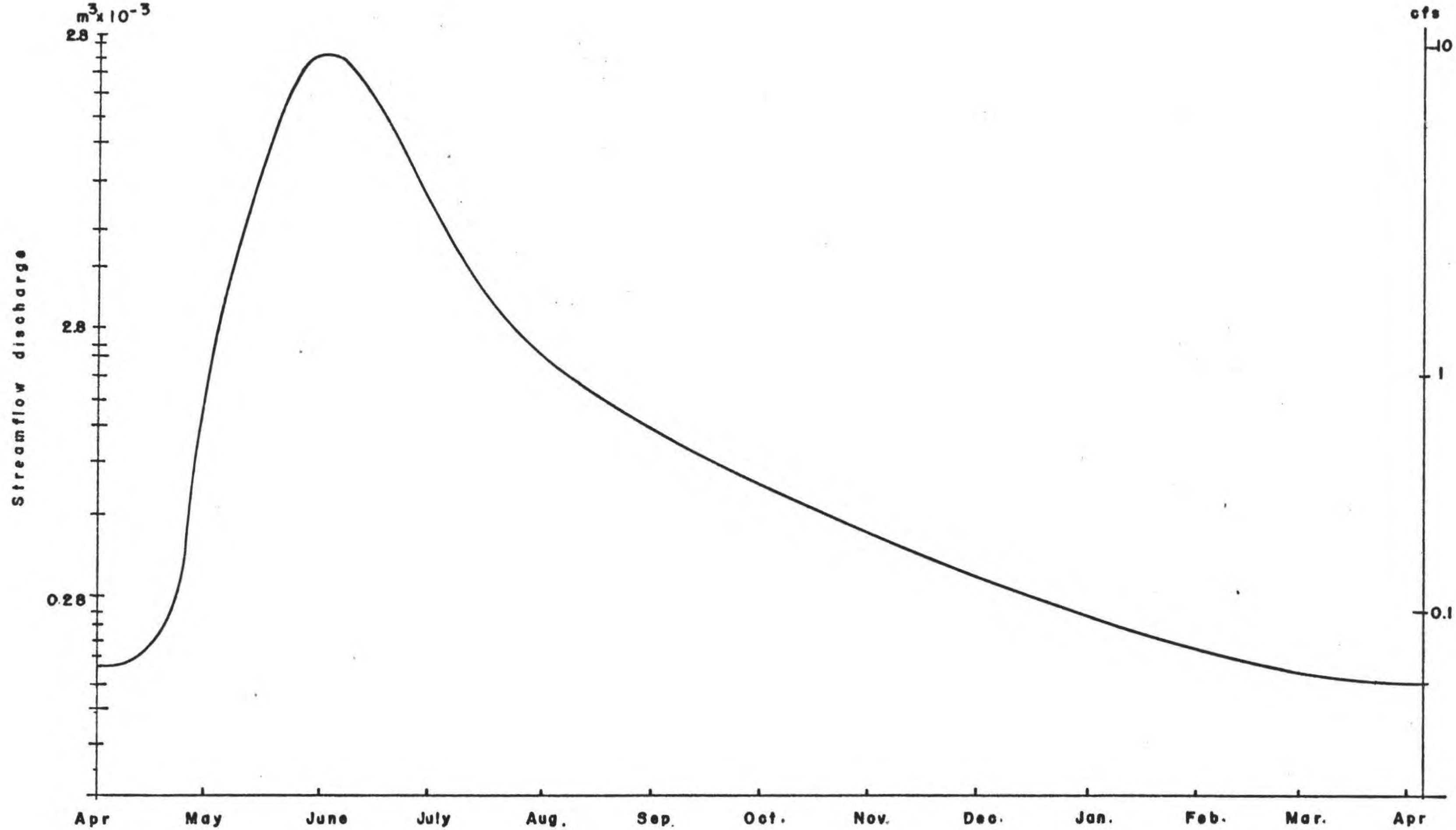

Fig.8 Streamflow hydrograph of the Upper Little Beaver Creek for an average of 3 years (1962-64)

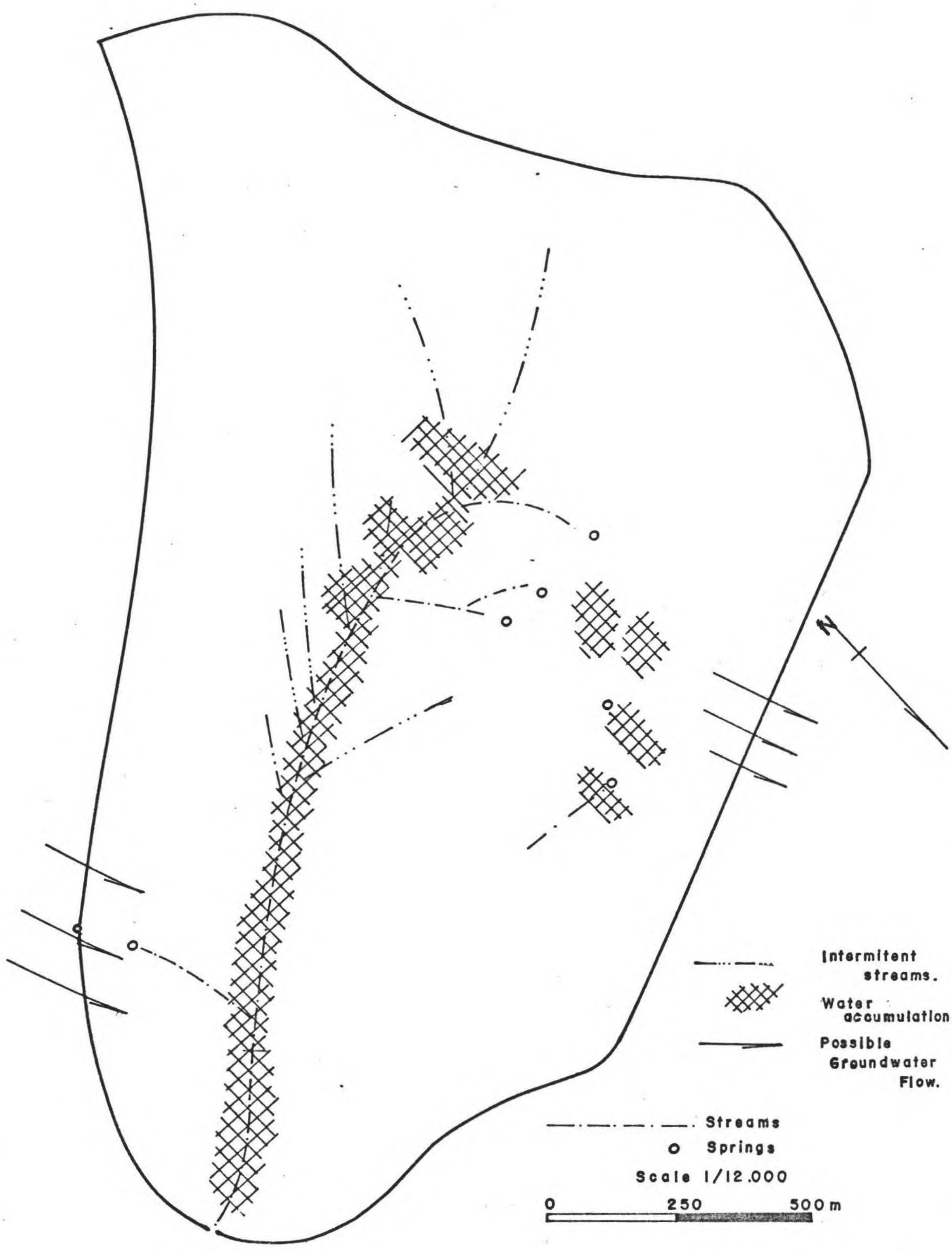

Fig. 9 Spring location and drainage characteristics.

On the north-facing slope, above the gauging station, a spring which flows all summer was also recorded. It appears to have its origin from water infiltrating the watershed located south of the study area. The spring emerges very close to the top of the ridge and there is no indication of zones of water accumulation above it within the study watershed.

These observations indicated that the influence of groundwater movement in the hydrologic behavior of the area is of primary importance.

Geology

A very general study of the geology of the area of study was made by Lovering and Goddard (1950). A map published by these authors shows the Upper Little Beaver Creek watershed lying in the contact zone of the schists of the metamorphic Idaho Spring formation and the intrusion of the silver plume granite.

The work done by Lovering and Goddard has proved to be slightly inaccurate when detailed geological surveys were carried out in areas mapped by them close to Upper Little Beaver Creek watershed in the Little South Fork watershed. These studies were implemented by: Kirst, P. W. (1966), Luther, F. R. (1968), Beck, L. D. (1969) and Muscalo, D. (1969).

In the lower part of the Little Beaver Creek they found areas of biotite, gneiss, schist, granite, felsic gneiss, and deposits of andesite.

Glaciation did not occur on the study area and, as a result, the slopes of the alpine zone do not show any steep cirque-type topography.

According to Keller (1963) and from data recorded in the field, all the transitions from schist to granite are present in the area. These materials are, in general, strongly weathered, and broken bedrock is common. Along the stream bottom, alluvial and colluvial debris has accumulated on top of the bedrock.

Soils

Keller (1963) described 8 soil profiles located along a transect which covered about 20% of the lower part of the Upper Little Beaver Creek watershed. With the study of 12 new profiles (Table A) a soil map of the watershed was made (Fig. 10).

Five distinct soil types were found in the area and classified according to Johnson and Cline (1965). They are: Podzols, Alpine Turf, Alpine Meadow, Bog Soils, and Lithosols. Fig. 11 shows a typical profile of each.

Podzols.- Podzols are represented by profiles No. 1D, 2D, 3D, 11D and 12D of the present study and profiles 1K to 8K studied by Keller (1963). Profile 1D is presented in Figs. 13 and 14.

Podzols are by far the dominant soils of the study area, covering 41% of the watershed (95.9 Ha). They range in altitude from 3,048 m (10,000 feet) to 3,353 m (11,000 feet). They are located along the main stream and on the north- and east-facing slope of the subalpine area. Keller and the author noted marked variation among the profiles in total depth, thickness of horizons, acidity, bulk density and stoniness with variation of slopes. All the profiles were characterized by a sandy loam to loamy sand texture. Keller analyzed the hydrologic characteristics of the podzols located in the lower part of the study

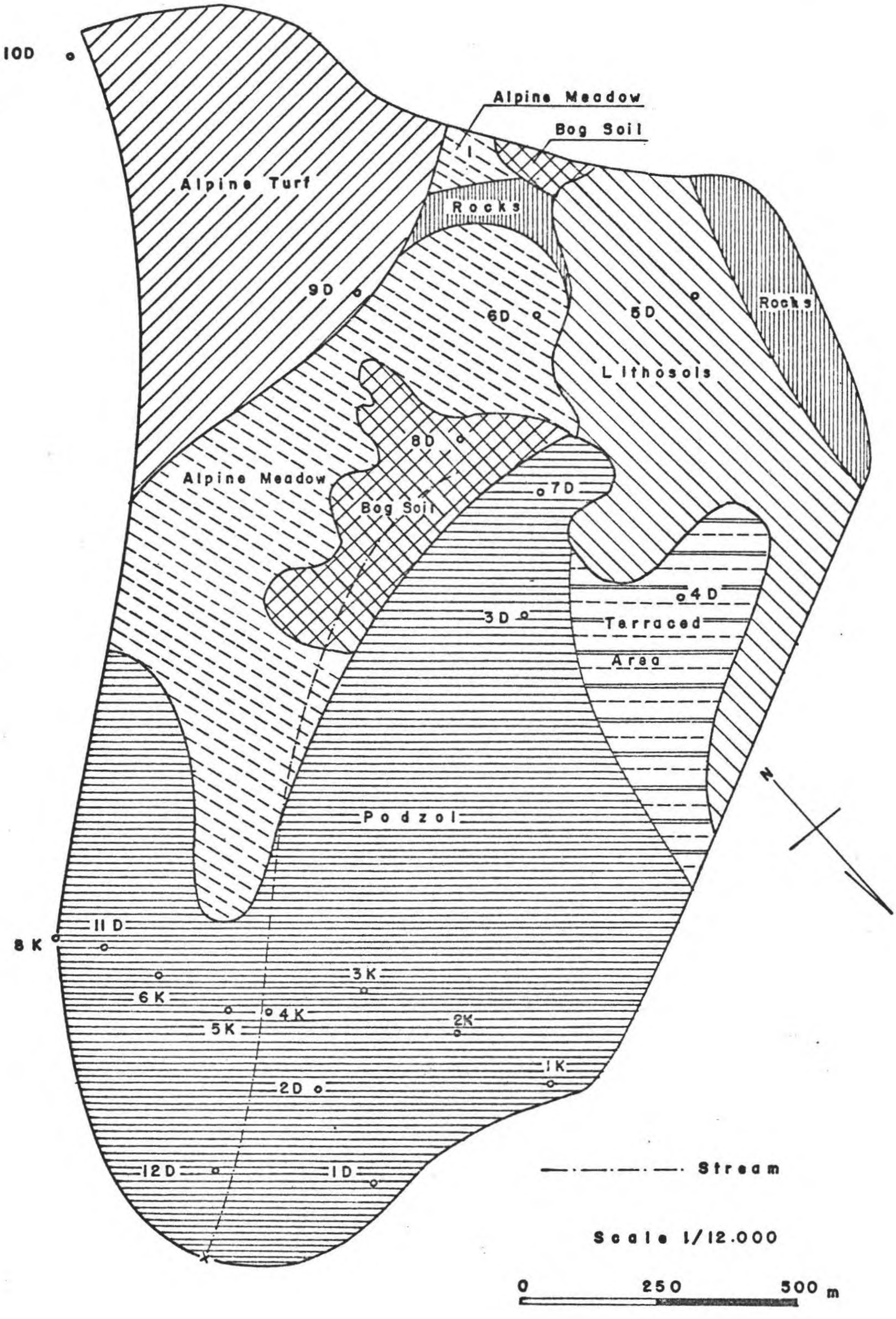

Fig. 10 Soil map and soilpit location.

watershed and found that their water storage capacity decreased with increase in elevation above the main stream.

Alpine Meadow.- Profiles No. 6A and Figs. 15 and 16 are representative of alpine meadow soils. They occupy the lower and concave areas formed by the slopes of Crown Mountain and Crown Point and the relatively level areas located on the north-facing slopes. They cover an area of 37.3 Ha, 16% of the watershed. These soils are closely associated with alpine turf soils (located on the slope of Crown Mountain), lithosols (located on the slope of Crown Point) and bog soils which are found in the same areas occupied by them but where the drainage is very poor.

Alpine meadow soils are characterized by A-C profiles (Figs. 15 and 21). The A layer in some areas has been completely eroded. They occupy even and smooth slopes averaging 10 to 20 per cent. On the strip terraces (Fig. 31) these soils alternate with bog soils.

Alpine turf.- Alpine turf soils are represented by profiles 9A and 10A and Figs. 17 and 18. They are located on the convex slopes of Crown Point covering 14% of the watershed (32.8 Ha). They range in elevation from 3,355 m (11,000 feet) to 3,745 m (11,420 feet). The topography is smooth, with an average slope of 20 to 30%. The slopes are also characterized by elongated rolling terraces which give a definite strip pattern to the vegetation. These soils have an A dark horizon, somewhat compacted which is believed to be due to sheep grazing in the area; a rocky A2 horizon and a B2ir horizon in which roots penetrate to 50 cm depth. The C layer is composed of highly weathered and deep materials, mainly schist.

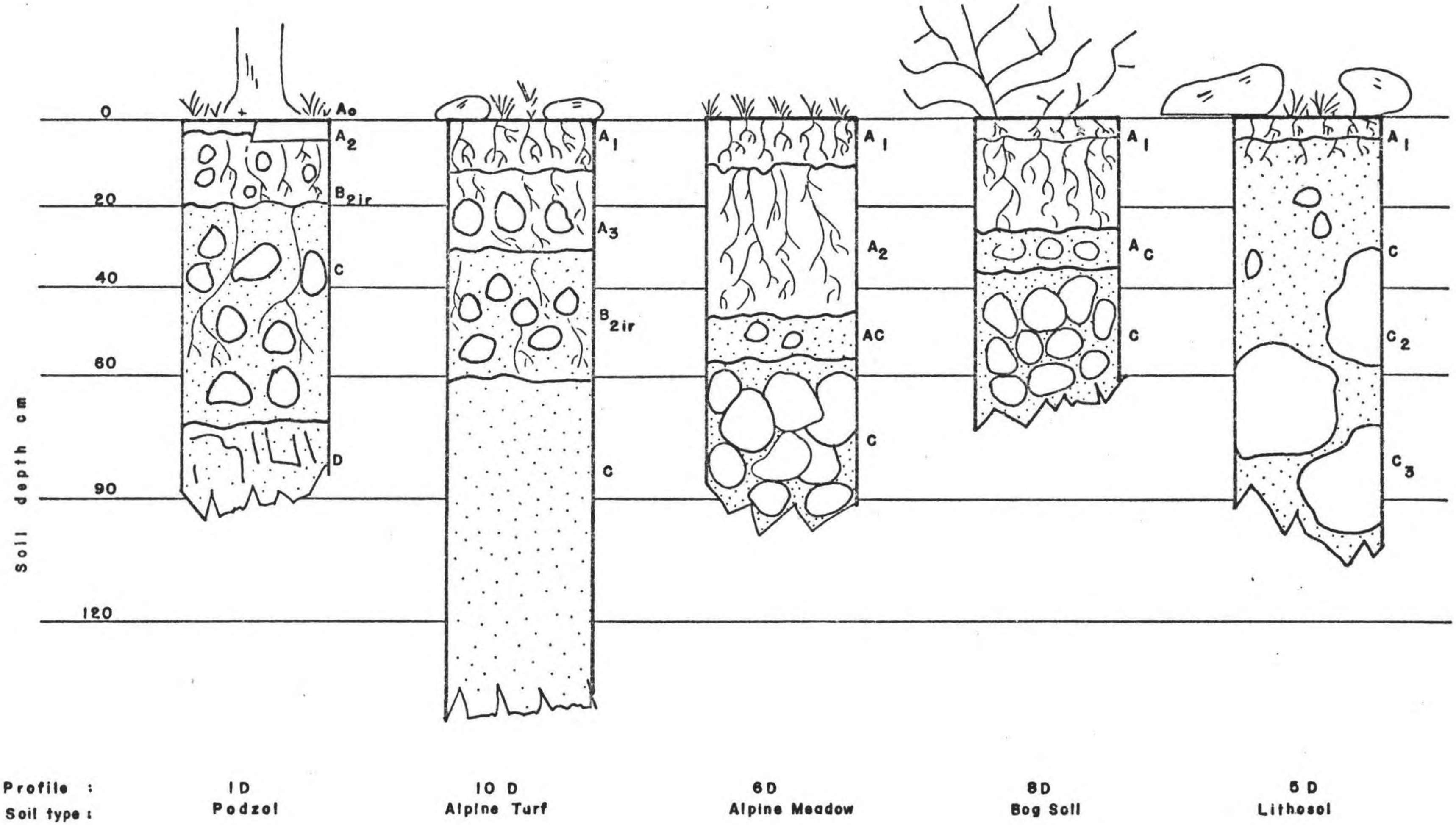

Fig.11 Representative profiles of five soil types present in the area of study.

Bog soils.- Bog soils, represented by the profile No. 8D, are located in the lower part of the concave area (Fig. 15) and on the upper part of the east-facing slopes along the terraces (Fig. 21). They cover an area of 10.0 Ha; 5% of the watershed. These soils are characterized by their poor drainage. Profile 8D shows the water table at only 35 cms below the surface. In other areas, free water is present at the surface. Bog soils are associated with springs and hydrophytic vegetation.

Lithosols.- Lithosols are represented by profile No. 5D (Figs. 19 and 20) which is located on the east-facing slope near Crown Point. They are characterized by a slightly darkened A horizon and a C horizon which varies in depth and compaction. The surface and the profiles of these soils are very stony (70% - 80%).

Rocks.- Rocks cover 8.7 Ha, 4% of the watershed. Their size varies from big boulders with a diameter of 1 to 2 m to small stones of less than 30 cm.

Vegetation

Vegetation of the Upper Little Beaver Creek is characterized by the influence of three climatic zones: Subalpine, Transition and Alpine.

On the subalpine area the vegetation is typical of the spruce-fir belt. The forest is under relatively undisturbed conditions with the exception of some zones which show the effect of an old fire. The canopy cover varies according to its position on the slope and the aspect of the slope. The denser canopies are on the bottom along the stream and on the north-facing slopes above the gauging station.

In the transition belt the vegetation is characterized by its irregularity. Patches of trees alternate with areas covered by herbs, grasses and shrubs. Association of poorly drained areas with willows (Salix sp) is common on the gently sloping aspects.

On the alpine area the major plants recorded were sedges, grasses, dwarf shrubs and cushion plants. Some scattered trees heavily deformed by winds, were also found. The relative distribution of vegetation and the percent of watershed area covered by trees are shown in Fig. 12 A brief discussion of this figure follows:

Vegetation Unit 1.- (Fig. 17) Alpine and transition belt; 73.45 Ha; 31.8% of the watershed; mostly covered by herbs: Geum turbinatum, Silene acaulis, Arenaria obstusiloba, Potentilla sp; grasses: Trisetum spicatum, Poa sp; shrubs: Salix sp and rushes: Carex sp. Scattered trees, Picea engelmannii and Abies lasiocarpa, are found in the lower part of this zone.

Vegetation Unit 2.- (Fig. 15) Transition belt; 13.70 Ha; 5.9% of the watershed; covered by willows (Salix sp) and associated with bog areas.

Vegetation Unit 3.- (Fig. 19) Alpine area, east-facing slope; 15.65 Ha; 6.8% of the watershed; rocks cover 60 to 70% of the ground; trees, Abies lasiocarpa and Picea engelmannii, are scattered, forming patches heavily deformed by wind. The ground vegetation consists of Trisetum spicatum, Arenaria obtusiloba, Silene acaulis, Geum turbinatum, Dryas octopetala and Carex sp.

Vegetation Unit 4.- Alpine area; top of the east-facing ridge; 7.87 Ha; 3.4% of the watershed; similar vegetation to Zone 3, but completely devoid of trees; 90% of the ground covered by rocks.

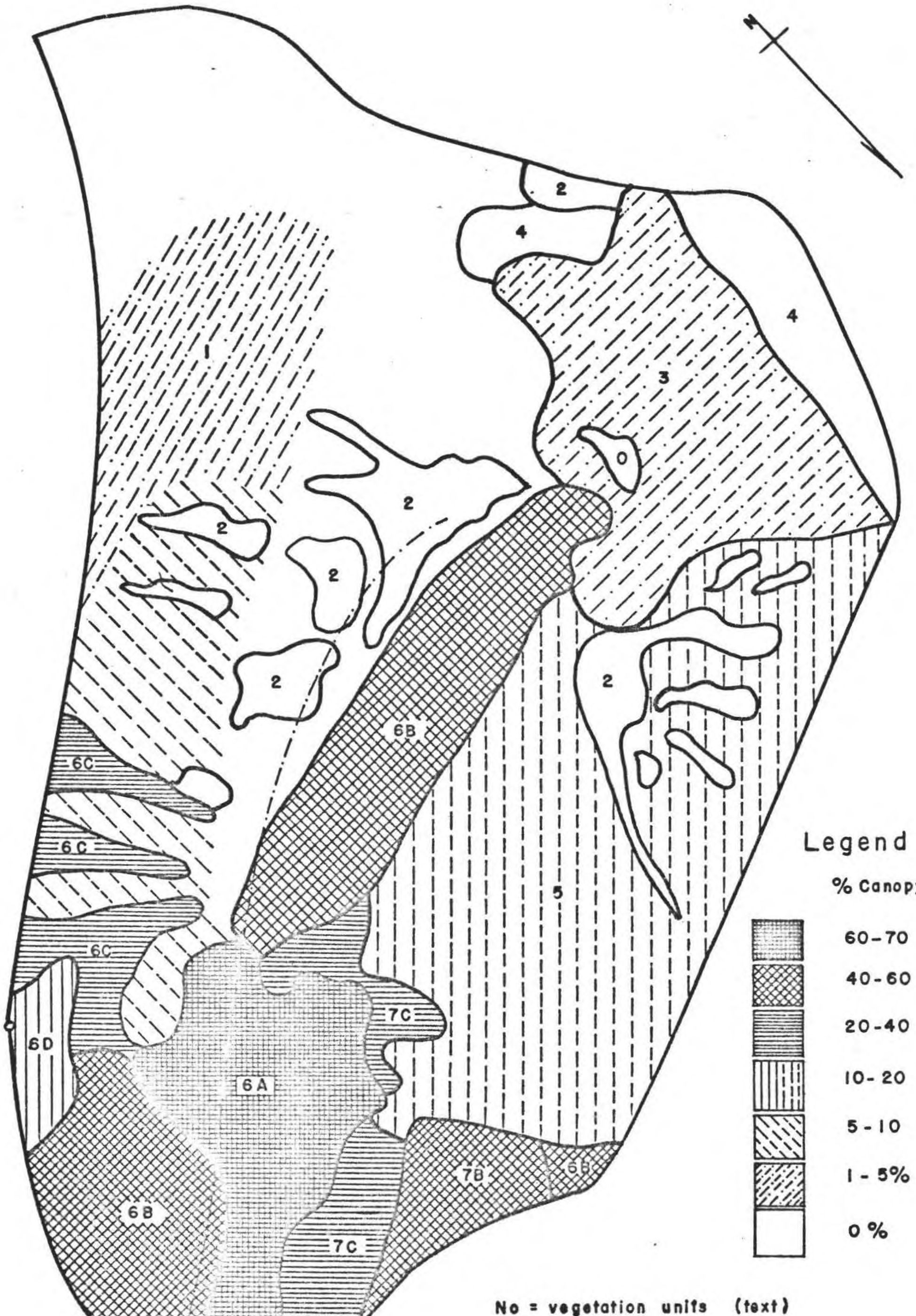

Fig. 12 Vegetation unit map and canopy cover.

Vegetation Unit 5.- (Fig. 21) Transition area, east-facing slope; 50.38 Ha; 21.8% of the watershed; complex zone with presence of terraces on the upper part. This area shows the effect of an old burn (C. 1900). Trees, *Picea engelmannii* and *Abies lasiocarpa* are scattered and reproducing by layers. Herbs, rushes, grasses and shrubs present include: *Geum turbinatum*, *Potentilla sp*, *Poligonum distortoides*, *Carex sp*, *Juncus sp*, *Poa sp*, *Festuca ovina bachyphylla*, *Trisetum spicatum* and *Juniperus communis*.

Vegetation Unit 6.- Subalpine area, 58.33 Ha; 25.3% of the watershed. This zone has been subdivided into 6A, 6B, 6C and 6D according to the density of stand formed by *Abies lasiocarpa* and *Picea engelmannii* as follows:

No.	Area	Percent of watershed	Canopy Cover
6A	11.84 Ha	5.1%	well developed 60-70%
6B	26.74 Ha	11.6%	medium in development
6C	7.82 Ha	3.4%	poorly developed 20-40%
6D	11.93 Ha	5.2%	burned area 10-20%

Vaccinium sp. is the most common plant present in the area. Other species include: *Juncus sp*, *Carex sp*, *Achillea lanulosa*, *Festuca ovina*, *Stipa lettermanin*, *Galium boreale*, *Salix sp*, *Juniperus communis* and *Ribes montigenus*.

Vegetation Unit 7.- (Fig. 13) Subalpine area, east-facing slope; 11.52 Ha; 5% of the watershed; zone covered by *Abies lasiocarpa*, *Picea engelmannii*, *Pinus contorta* and very small patches of *Populus tremuloides*. *Pinus contorta* is the dominant species in some areas. The zone has been divided according to variations in canopy cover.

No.	Area	Percent of watershed	Canopy Cover
7B	3.72	1.6%	medium in development
7C	7.80	3.4%	poorly developed 20-40%

Fig. 13 East-facing slope - site of profile 1 D

Fig. 14 Podzol - profile 1 D

Fig. 15 a) Alpine meadow soil subject to erosion - site of profile 6 D
b) Bog soil - site of profile 8 D

Fig. 16 Alpine meadow soil - profile 6 D

Fig. 17 Crown Mountain, northeast facing slope

Fig. 18 Alpine turf - profile 10 D

Fig. 19 East-facing slope - site of profile 5 D

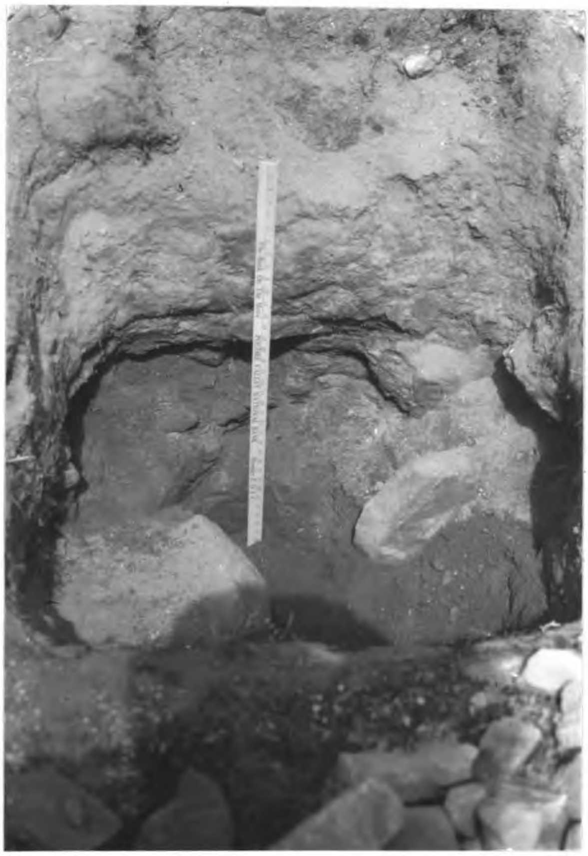

Fig. 20 Lithosols - profile 5 D

Fig. 21 Terraced area - site of profile 4 D

Fig. 22 Alpine meadow soil in terraced area - profile 4 D

Fig. 23 Strip terraces area - site of profile 3 D

Fig. 24 Podzols - profile 3 D

Chapter IV

ANALYSIS OF THE HYDROLOGIC SOIL CHARACTERISTICS

The study of the hydrologic soil characteristics of the Upper Little Beaver Creek was divided into three parts: 1) Selection of the representative soil profiles, 2) Field and laboratory analysis and 3) Storage and infiltration calculations.

Selection of the soil profiles

Based on the results presented in Chapter III, a total of twelve new soil profiles were judged to be the minimum required to determine variations in hydrologic soil properties.

Field and laboratory analysis

Field cards based on the formats used by the U. S. Forest Service (FSH, 2500-3 and FSH, 2559.2, 1969) were used to describe characteristics of each profile. Vegetation, topography, erosion and drainage were also recorded.

Loose samples from each horizon were taken for laboratory analysis of texture, moisture tension relationships, and color. Core samples were taken from five profiles giving a total of 48 with two to three repetitions for each horizon. Core samples were very difficult to obtain due to the extreme stoniness of the area. The size of the cores used was 3.9 cm long by 2.5 cm wide. Bulk density was directly measured on the field from each horizon using a soiltest volumeasure. The procedure was to cut the side of the profile, forming steps on each of the horizons (Fig. 24). Bulk density was calculated considering gravel and stones up to 250 mm in diameter. The average distribution was as follows: 70% particles less than 2 mm, 20% between 2 and 5 mm and 10% between 5 mm and 250 mm in diameter.

In the laboratory the amount of sand, silt and clay was calculated using the hydrometer method (Amer. Soc. of Agron., 1965). The color of the soils (dry and wet) was determined using the Munsell Soil Color Chart. Soil moisture at 15 bars was obtained with a pressure membrane apparatus using the methods outlined by Richards (1954) and using samples sieved to a 2 mm diameter. Soil moisture at 1/10 and 1/3 bar was measured using a porous plate. Undisturbed samples were used in the latter two measurements in order to include the effect of soil structure. All the calculations were made in triplicate.

The hydraulic conductivity of the core samples was determined using the facilities of the Porous Media Laboratory located at the Foothills Research Center of Colorado State University.[1/] The tests were made with undisturbed, completely saturated samples (Amer. Soc. of Agron., 1965).

Storage and hydraulic conductivity calculations

The storage calculations were based on the methods presented by Holton (1967). The potential storage capacity was divided into three classes: 1) detention storage, which is the water held between field capacity (0.33 bar) and saturation point, 2) retention storage, which is the water held in the soil at field capacity (0.33 bar) and 3) water available for plants, which is the water held between field capacity (0.33 bar) and wilting point (15 bars). The amount of water

1/ Thanks to the collaboration of Harold Duke, A.R.S.

present in each of these classes was expressed in cm of water per cm of soil depth.

The values of moisture retention of the soil, measured at tensions of 0.33 bar and 15 bars, and expressed as percent of moisture by weight were converted to percent of moisture by volume by multiplying them by bulk density:

$$\frac{\text{weight of water (g)}}{\text{weight of dry soil (g)}} \text{x100} \times \frac{\text{weight of dry soil (g)}}{\text{volume of dry soil (cm}^3\text{)}} =$$

$$\frac{\text{volume of water (cm}^3\text{)}}{\text{volume of dry soil (cm}^3\text{)}}$$

The resultant values were then multiplied by the depth of each horizon (in cm), giving the amount of water in cm that each horizon holds at 0.33 bar and 15 bars. The former value is, according to the previous definition, equal to the water retention. The difference between the two figures is the water available for plants. Both values were then corrected for stoniness (expressed as the percent of volume of the soil occupied by rocks with a diameter bigger than 250 mm).

In order to calculate water detention, porosity was first obtained from its relationship with bulk density and particle density, assuming the latter value as being equal to 2.65 g/cm^3 for the layers without organic matter and 1.2 g/cm^3 for the layers with mixed minerals and organic matter (Lutz, 1947; Amer. Soc. of Agron., 1965). The following formula was used:

$$\text{Porosity} = 1 - \frac{\text{Bulk density (g/cm}^3\text{)}}{\text{Particle density (g/cm}^3\text{)}}$$

The porosity, expressed as percent per volume, was then assumed to be equal to the volume occupied by water when the soil is completely

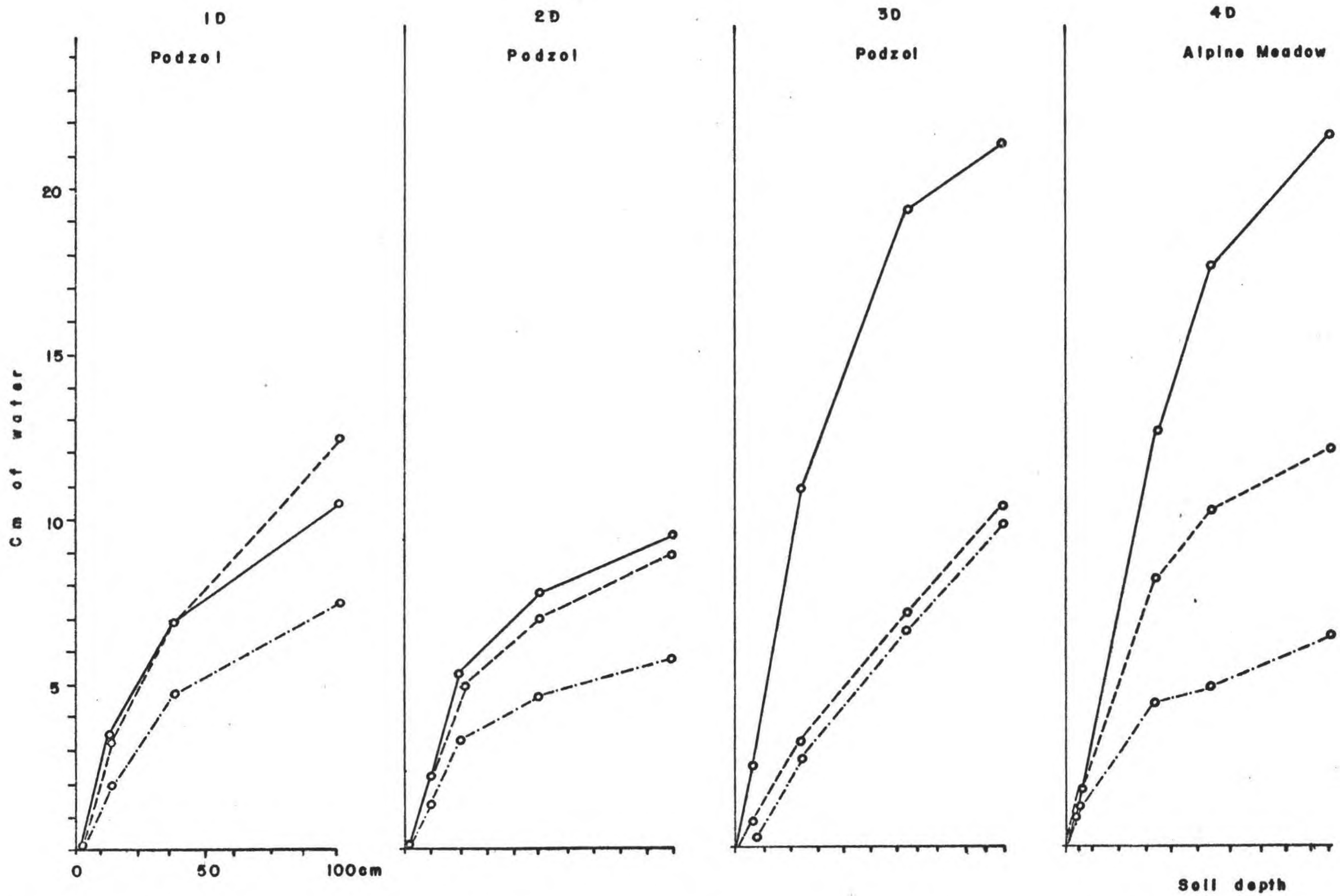

Fig. 25 Detention (o——o), retention (o-----o) and water available for plants (o-·-·-o) in representative soil profiles.

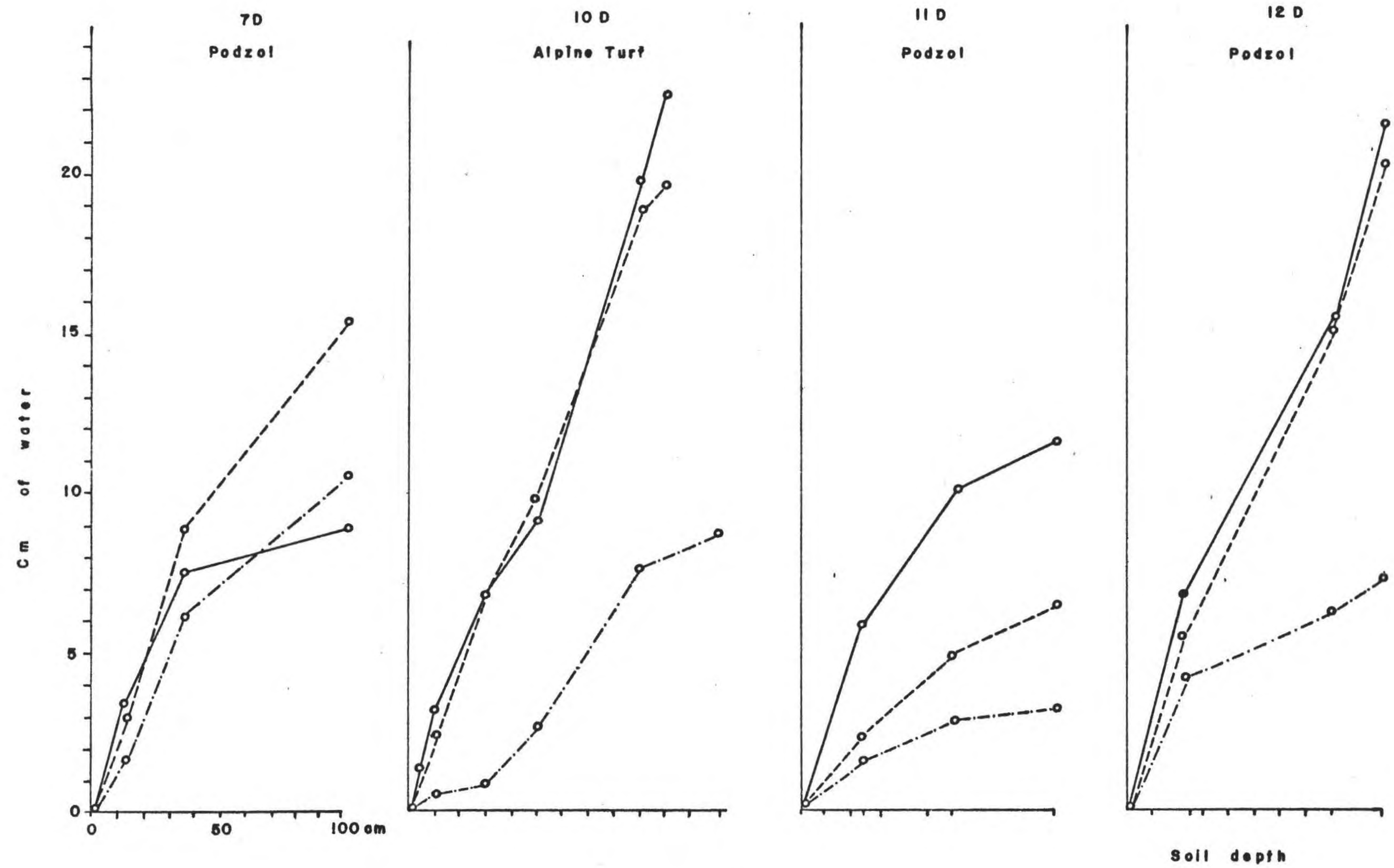

Fig. 25 Continued

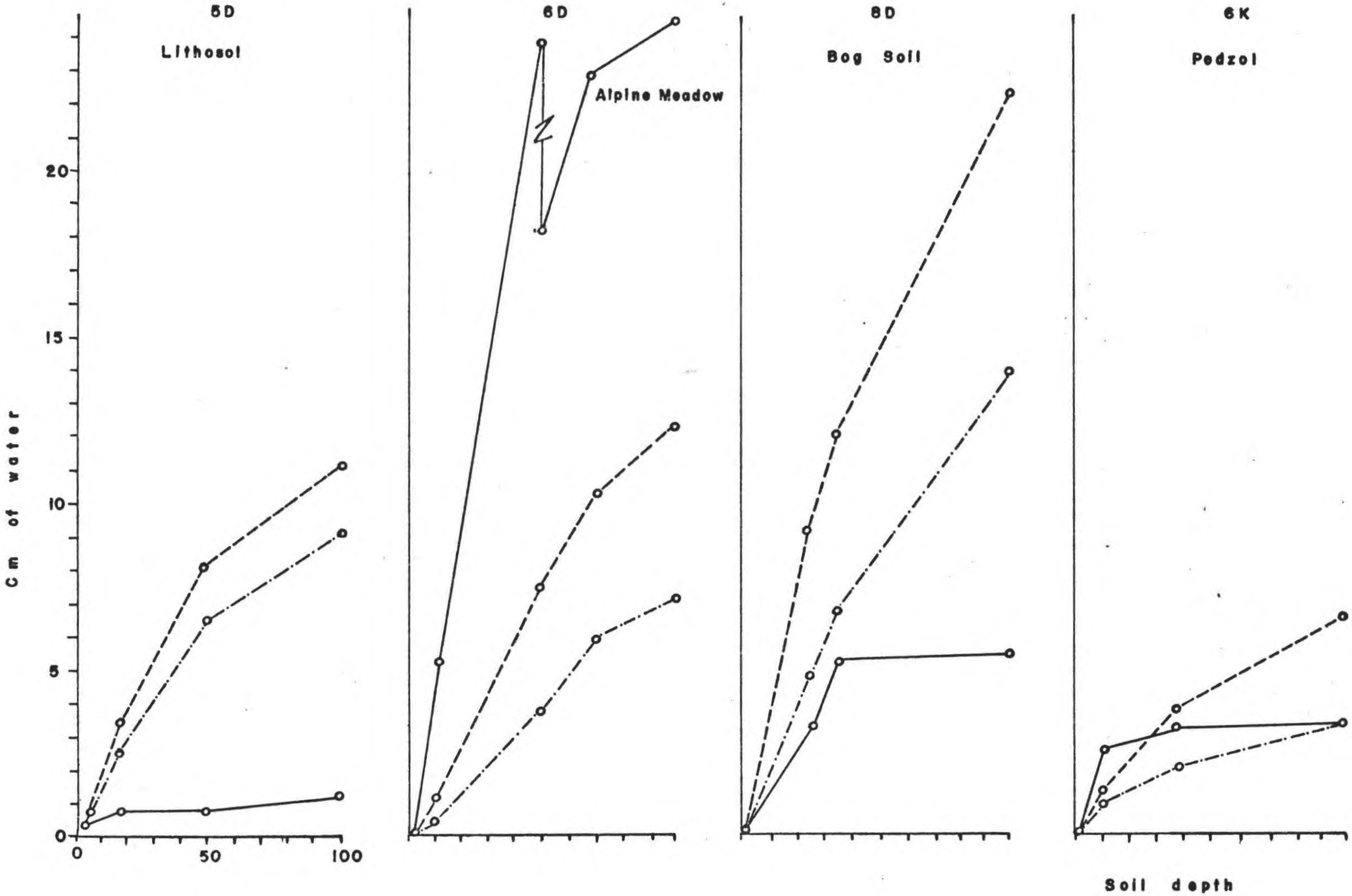

Fig. 25 Continued.

saturated. Following the same procedure as outlined previously, the calculated volumes were converted to cm of water per cm depth of soil and corrected for stoniness. Detention capacity was then calculated subtracting the values obtained for retention capacity from the above values. The procedure can be followed in Table C in the appendix using Table B as a reference for values of moisture at 1/3 bars, and at 15 bars and for percentage of stoniness.

Fig. 25 shows the relative distribution of detention storage, retention storage and of water available for plants in the different profiles. The following observations were made: 1) the values of detention storage capacity, retention storage capacity, and water available for plants are extremely variable from one profile to another and within the same soil type (Podzols being a striking example), 2) the relative distribution of the three types of storage are not equal from one profile to another. Profiles 1D, 2D, 10D and 12D show similar amounts of detention and retention. Profiles 5D, 6K, 7D and 8D evidence greater retention while 3D, 4D, 6D and 11D have greater detention. These results are believed to be caused by differences in stoniness, structure, texture and bulk density of the profiles. These characteristics, to a depth of one meter, vary considerably with the thickness of the A, B and C horizons.

Fig. 26 shows graphically the values of hydraulic conductivity obtained for the 5 profiles studied: 1D, 3D, 4D, 5D and 10D. Podzols and alpine meadow soils, represented by the first three profiles have a high hydraulic conductivity in their upper horizons (up to 67 cm/hr.) in contrast with the low hydraulic conductivity of lithosols and alpine

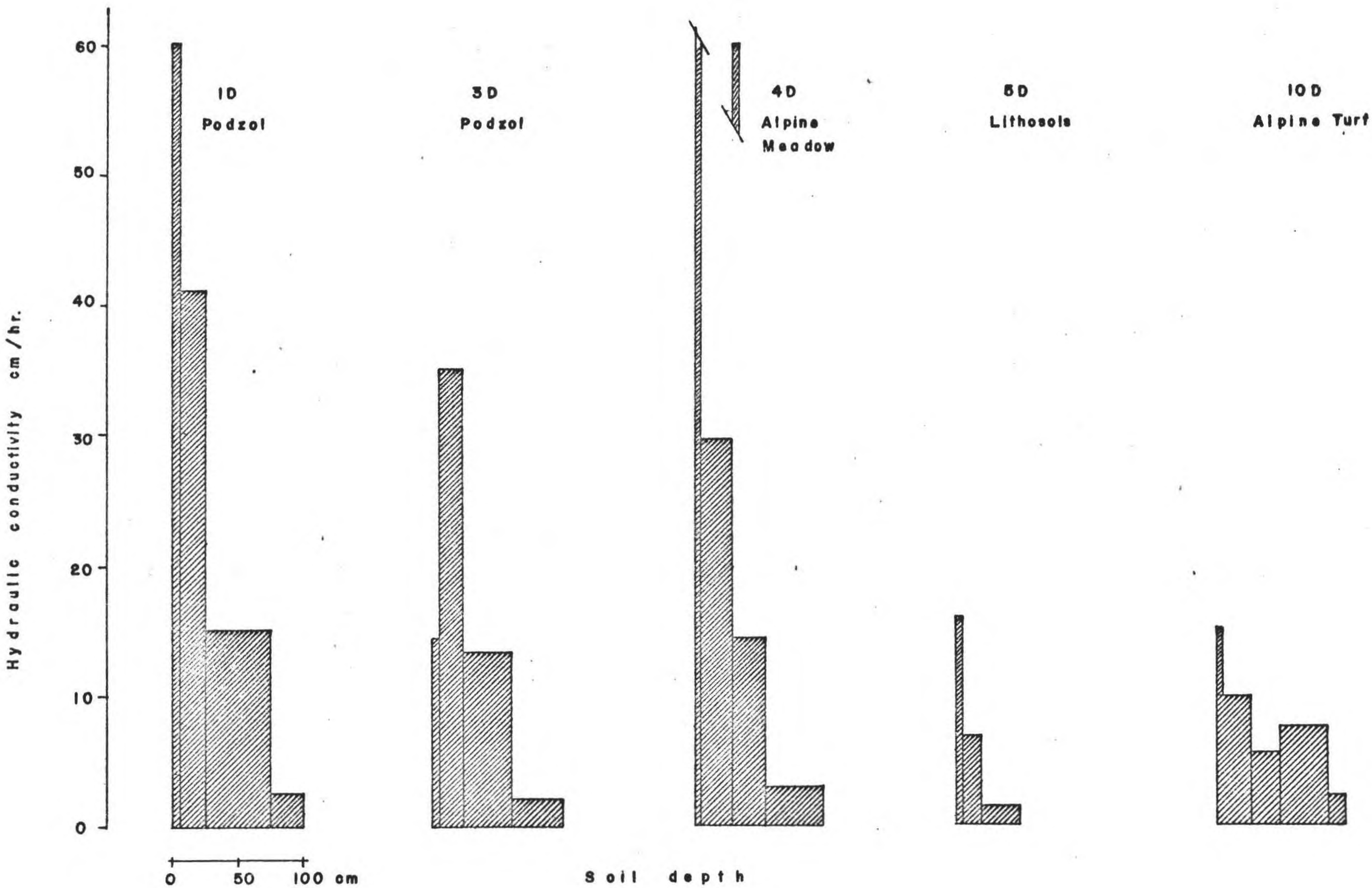

Fig. 26 Hydraulic conductivity of 5 profiles.

turf soils (16 cm/hr.). The 5 profiles show decreases in their hydraulic conductivity with depth at 50 to 100 cm they average 2 to 3 cm/hr. indicating a possible continuous slow percolation toward deeper strata.

Although determination of statistical relations between the various soil properties measured was not a major objective of this study, the data obtained were analyzed for possible relation with water storage capacity. The tests were:

Texture versus water retention storage capacity.

Texture versus water detention storage capacity.

Bulk density versus water retention storage capacity.

Bulk density versus water detention storage capacity.

A correlation was found between the values of bulk density and water detention capacity (as calculated in the previous section) of all the studied horizons with the exception of the ones where the estimated particle density was less than 2.65 g/cm^3.

Fifty values of both variables fell into the above category representing all the profiles (14) and soil types studied (4). The test of correlation gave the following results:

a) Equation of estimated correlation:

$$Y = 7.52 - 3.63X$$

where:

Y = water detention capacity (calculated following the methods outlined in the previous section and considering only soils with average particle density of 2.65 cm^3) expressed in cm of water per 10 cm of soil depth.

X = bulk density (calculated for soils with average particles of 80% less than 2 mm, 20% between 2 mm and 5 mm, and 10% between 5 mm and 250 mm) expressed in cm^3.

b) Regression coefficient = 0.89

c) Standard deviation Y/X = 0.679 cm water/10 cm soil depth.

d) Maximum deviation positive = 1.59 cm water/10 cm soil depth.

e) Maximum deviation negative = 1.15 cm water/10 cm soil depth.

The established correlation is graphically presented in Fig. 27. Retention storage capacity can be evaluated from the values of total porosity (obtained from bulk density) and the calculated values of water detention storage capacity.

The following observations with respect to the equation were made in order to indicate its reliability and its possibility of improvement. The recommendations listed were not attempted because of lack of data.

1. The percent of distribution of particles in the size classes used in determining bulk density (less than 2 mm diameter, 2 mm to 5 mm diameter and 5 mm to 250 mm diameter) was considered uniform for all samples. It is probable that the exact measurement and inclusion of the actual percent distribution of particles in calculation of bulk density will improve the prediction formula.

2. The measurements of moisture retention at 0.33 bar were made on undisturbed samples containing stones with average maximum diameters of 10 mm while bulk density was measured in samples including stones with a maximum diameter of 250 mm. This is another possible factor of variation which in other studies can be avoided.

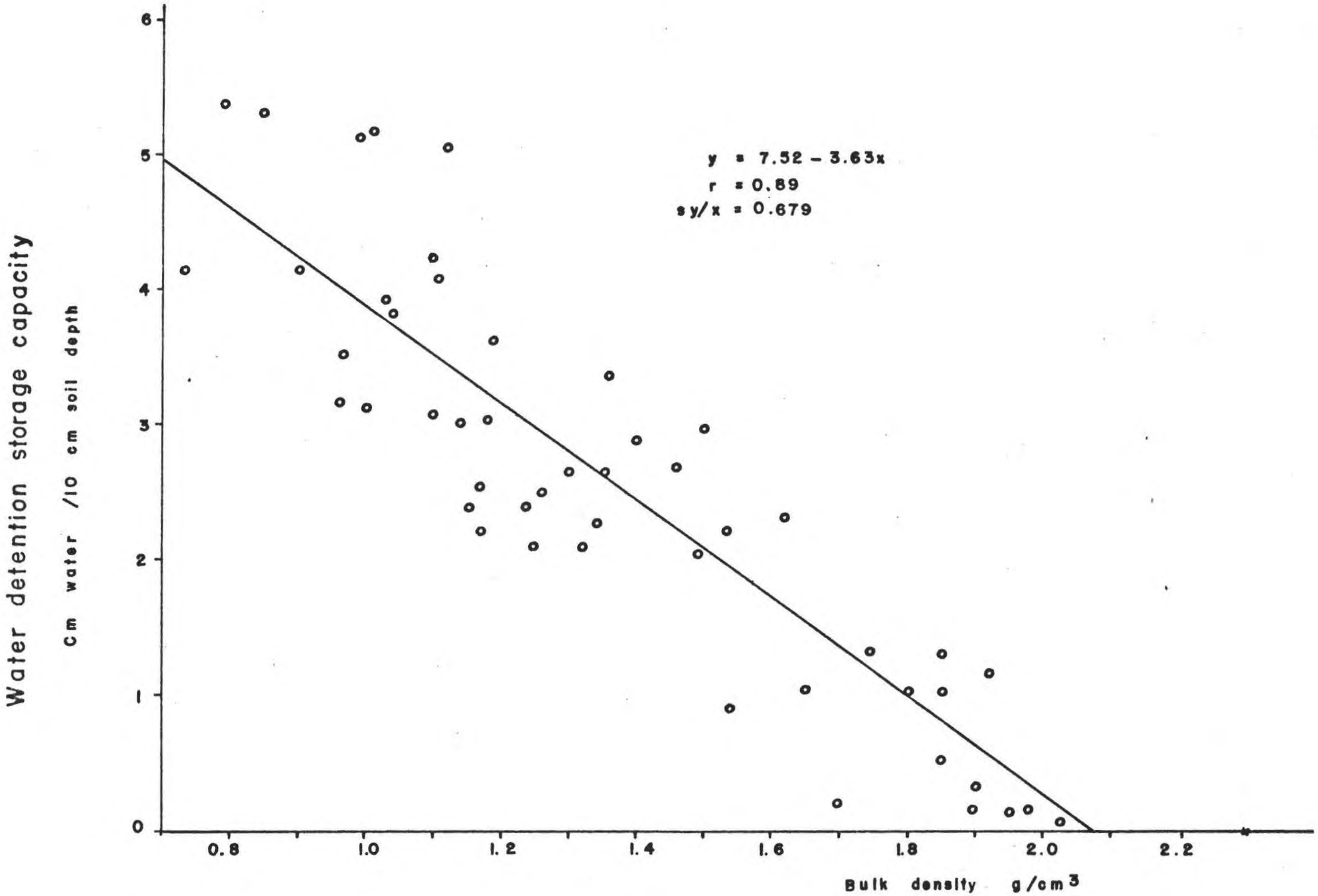

Fig. 27 Relation of water detention storage capacity to bulk density.

3. The standard error of 0.679 is considered adequate for the approach used in the estimation of detention capacity in the area since the calculated values must be corrected for stoniness (percent of stones bigger than 250 mm) in order to obtain actual detention storage capacity. This degree of stoniness is variable and difficult to estimate, and consequently can easily introduce more errors than the ones involved in using the prediction equation.

Chapter V

HYDROLOGIC UNIT CLASSIFICATION

This chapter has been divided into two sections: 1) Relation of the hydrological soil properties to the physical characteristics of the watershed 2) Partitioning of the watershed into hydrologic units.

Relation of the hydrological soil properties to the physical characteristics of the watershed.

Determination of the physical characteristics of the watershed responsible for the differences in its hydrological soil properties.

The differences in hydrologic properties of the soils of the watershed were studied in relation to variations in horizon depth, stoniness, bulk density, structure, and texture to a depth of 1 m, (based on the relation between the hydrologic and physical soil properties of the soils as analyzed in Chapter IV). These variations were found to be caused by the following physical characteristics of the watershed: weathering process (rate and type), elevation, climate, microclimate, vegetation, slope, aspect and landform.

The parent material was found to be uniform for all the watershed and consisted of granite, schist, and gneiss. These materials under the influence of weathering processes were found to disintegrate principally into coarse sand, gravel and stones. The weathering process was evidently caused mainly by extreme changes in temperature, by vegetation and by water in the soil. The influence of these three factors was found to vary within the watershed thus accounting for the various soil types classified (Chapter III) and their variations in hydrologic characteristics.

On the upper part of the watershed, at elevations ranging from 3,353 to 3,487 m (11,000 to 11,440 feet), where few trees are present, aspect plays an important role in soil formation (Fig. 29). The east-facing slopes of Crown Point have shallow, stony and compacted soils with very low water storage capacity. In contrast, the soils located on the north- and northeast-facing slopes of Crown Mountain weathered more rapidly and are, therefore, deeper, finer textured with lower stoniness. They are well structured and have higher water storage capacity. The difference between rates of weathering on the various aspects of the area was believed to be due to greater water percolation from snowmelt on the north- and northeast-facing slopes.

On the lower part of the watershed at elevations ranging from 3,048 to 3,355 m (10,000 to 11,000 feet) the differences between the north- and east-facing slopes were not so marked because of the more uniform vegetation cover and the lesser effect of climate. The soils located in level areas in contrast have a deep A horizon and few stones in their upper horizon. They accumulate alluvial and/or colluvial material and have high water storage capacity.

Three types of level areas were found to induce variations in hydrologic characteristics of the watershed: the concave area located in the central part of the watershed, the strip terraces located on the upper part of the east-facing slopes and on the northeast-facing slopes, and the alluvial terraces along the main stream. The concave area is associated with bog soils, it has fine-textured soil accumulated by sedimentation. It shows high water retention storage capacity and low hydraulic conductivity. The strip terraces located on the east-facing slopes have deep soils and accumulate alluvial and colluvial

Fig. 28 General view of the upper area of study
a) east-facing slopes b) concave area
c) north-facing slopes

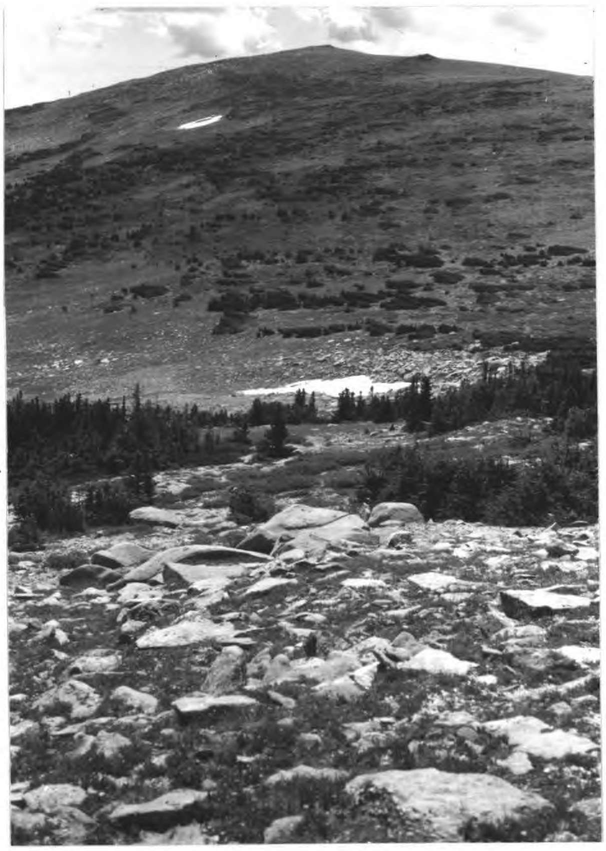

Fig. 29 Alpine area - contrast between
east- and north- facing slopes

Fig. 30 On the east-facing terraced area

Fig. 31 Bog area on the east-facing terraced area

Fig. 32 a) East-facing terraced area b) spring emerging below the terraces material eroded from their banks. They are also associated with bog soils and have high water storage capacity. The strip terraces located on the northeast-facing slopes are very narrow and do not show signs of surface water accumulation. They seem to be formed by a creep type of mass movement. These terraces also have deep soils and high water storage capacity. The alluvial terraces located along the main stream accumulate high quantities of colluvium from the north-facing slopes as well as alluvial material. These terraces have very deep soils, low stoniness and high water storage capacity.

The effect of vegetation on water storage capacity has been partially mentioned with respect to the weathering process. Vegetation affects also the bulk density, structure and texture of the upper horizons, varying their storage capacity and hydraulic conductivity.

From these observations it was concluded that:

1. The differences in the hydrologic properties of the soils are caused by the variations in the following physical characteristics of the watershed: weathering (rate and type), climate, vegetation, elevation, aspect, landform and slope.
2. The major soil types classified in the area: podzols, lithosols, alpine meadow, alpine turf and bog soils, reflect most of the variations in the physical characteristics of the watershed and consequently reflect also most of the variations in its hydrologic soil properties.
3. By separating the major soil types on the watershed, most of the hydrologic soil properties are taken into account due to the above relation.
4. When the same soil type has different slopes, aspects of landform within its boundaries, the separation of these variations also will

separate areas of equal hydrologic soil characteristics. Consequently, hydrologic units can be delineated by the separation.

Relationships between the physical characteristics and the hydrologic soil properties of the watershed.- The primary objective of this section was to relate quantitatively the hydrologic soil properties (hydraulic conductivity, water retention storage capacity and water detention storage capacity) to the physical characteristics of the watershed. These characteristics were found to introduce variations in their mentioned properties, specifically in soil types, average slope[1], landform slopes[2], and aspect.

Because of insufficient data on hydraulic conductivity, the only hydrologic soil properties used for the relationships were water retention and water detention storage capacity.

The values of retention and detention storage capacity were related to the average slope and landform slope in which they were measured. These relationships were made considering first all the soil types recorded on the watershed and secondly, considering only one soil type (Podzol).

The following correlations were made:

Considering all soil types and total water storage capacity (detention + retention storage capacity).

---

1. Average slope was defined as the slope of the area in which the measurement of the hydrologic soil properties was made. This slope was measured from the topographic map (Fig. 4) which has contour lines every 12.2 m. Consequently, landforms too small to be included in the map could not be considered.

2. Landform slope was defined as the slope at the sample site and was measured in the field, thus considering the landforms not included in the previous definition (strip terraces principally).

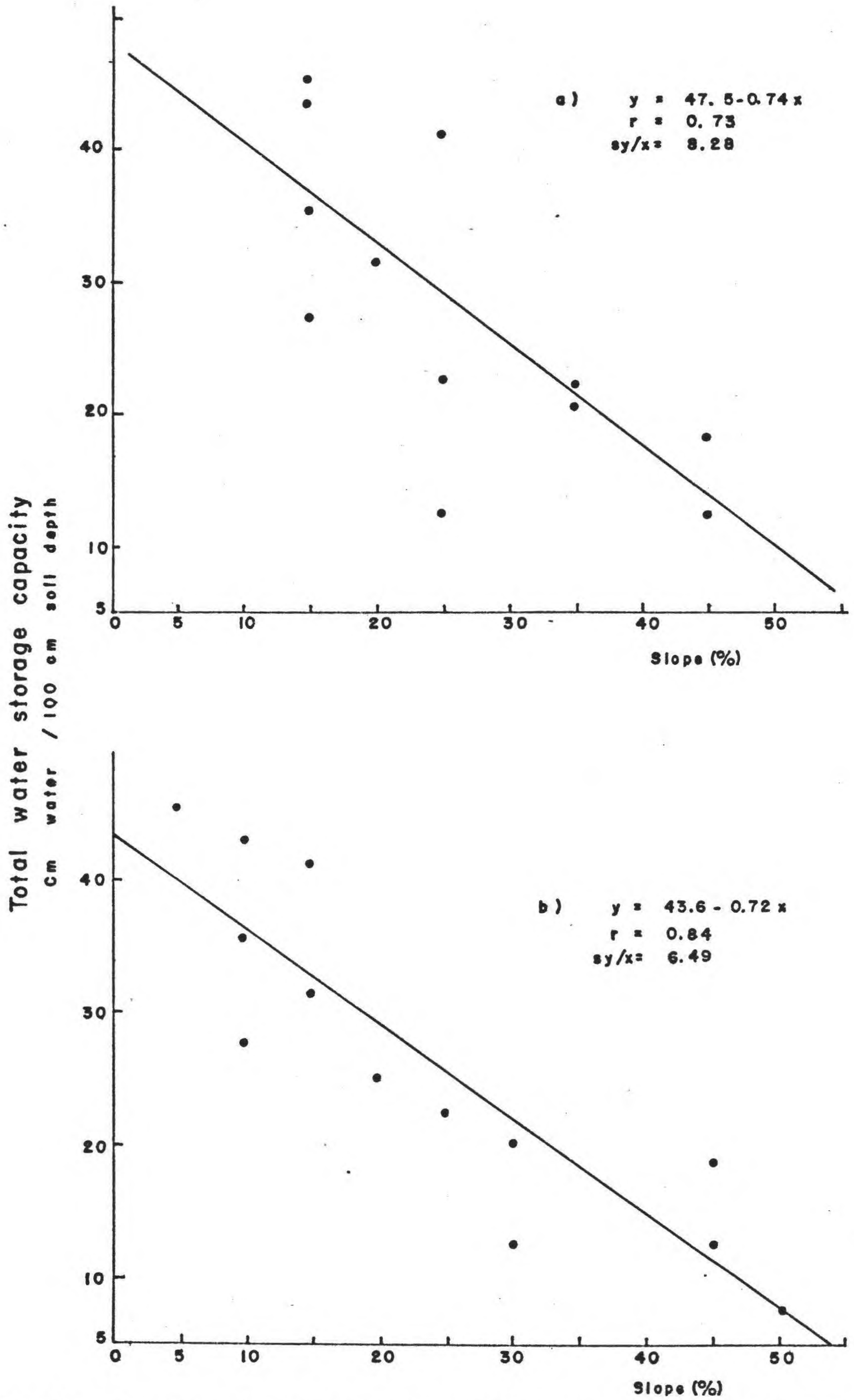

Fig. 33 Relation of water storage capacity to slope inclination on all soil types a. Average Slope b. Landform slope

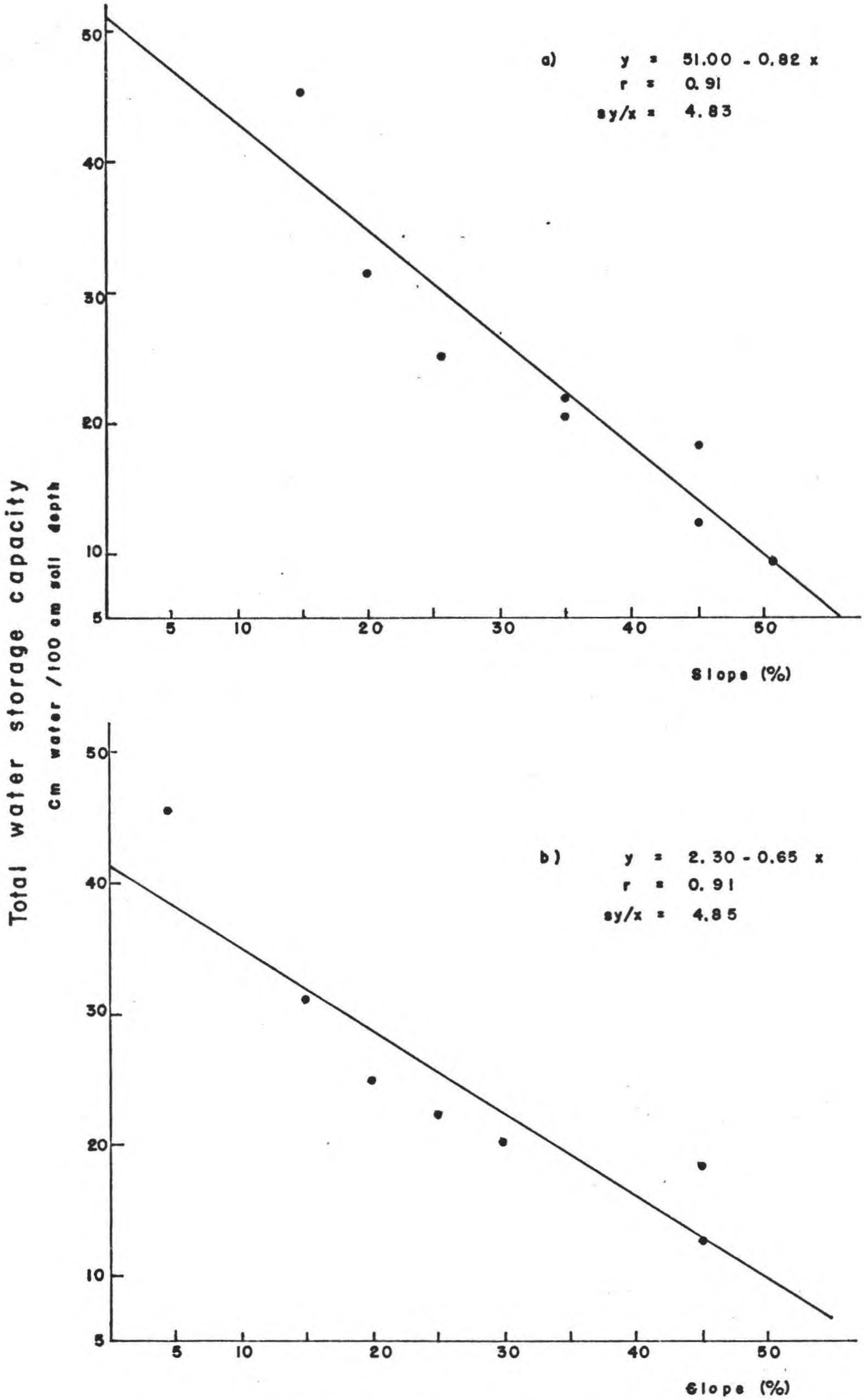

Fig. 34 Relation of water storage capacity to slope inclination on podzol
a. Average Slope b. Landform Slope

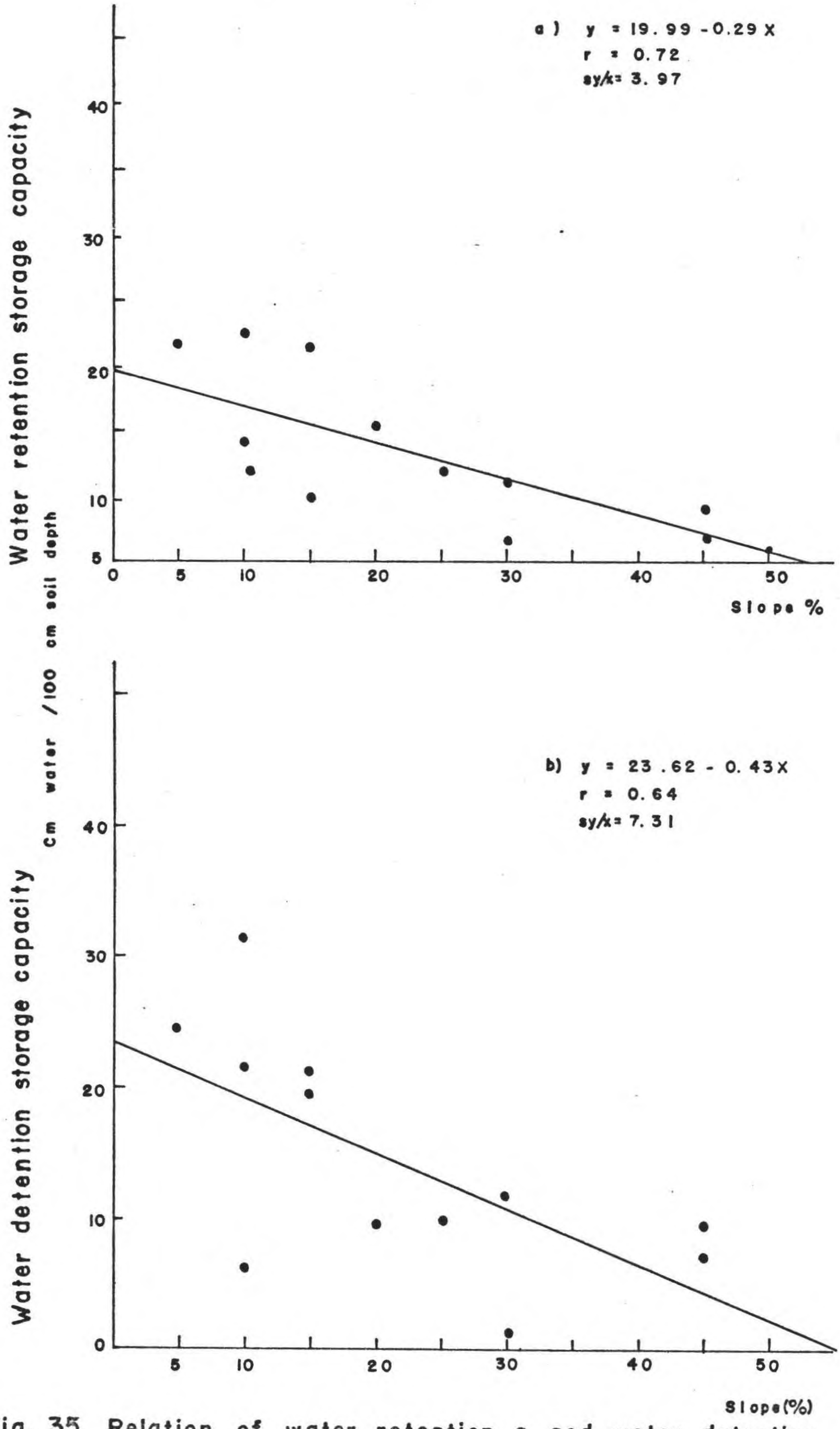

Fig. 35 Relation of water retention a. and water detention b. storage capacity to slope at the sample site on varying soil type

A.- Average slope versus total water storage capacity.

B.- Landform slope versus total water storage capacity.

Considering one soil type (Podzol) and total water storage capacity (detention + retention storage capacity).

C.- Average slope versus total water storage capacity.

D.- Landform slope versus total water storage capacity.

Considering all soil types and detention and retention storage capacity separately:

E.- Landform slope versus detention storage capacity.

F.- Landform slope versus retention storage capacity.

The effect of aspect could not be quantitatively analyzed due to the lack of sufficient data. The results of these correlations are presented in Table 1. The correlations obtained indicated that the physical characteristics of the watershed which principally affect the water storage capacity of the soils are: Soil types, average slope and landform slope. The influence of these factors on the hydrologic soil characteristics of the watershed has already been discussed in the previous section. The influence of aspect could only be considered by qualitative analysis which was also done in the previous section.

Delineation of the boundaries of the hydrologic units

The delineation of the boundaries of the hydrologic units was based on the analysis of the factors considered in the previous section. Consideration was given to soil types, slope, landform and aspect in successive steps. Vegetation was included among these factors.

The first step was to consider the soil types. It was assumed that each soil type represented a potential hydrologic unit. The soil map then represented the first hydrologic unit classification.

The second step was to consider the changes of slopes and aspect on the areas covered by each soil type. The study of the profiles of like soil types showed variations in both effective depth and horizon depth, variations of slope and aspect gave different storage capacities for each profile. It was considered that the limits of slope-change in each of the three aspects of the watershed were also the limits of change of effective depth and horizon depth of a soil type.

The assumption proved to be correct when more than one profile was studied under equal conditions of slope, aspect and soil type. This was done by field observations and by comparisons with profiles studied by Keller (1963). Aerial photos and the topographic map were used to delineate the boundaries of areas under the same degree of slope and soil type. The major changes in slope were found to be located on the lower part of the watershed, where it is V shaped (Fig. 5, cross-sections 1, 2 and 3). This area, previously classified entirely as podzol, was subdivided considering variations of slopes from 10 to 20% along the stream, 40 to 50% at middle slope, and 30 to 40% near the ridge and on both sides of the stream (in order to include aspect).

On the upper part of the watershed no partitioning on the basis of slope was necessary for the delineation of the hydrologic unit boundaries due to the fact that each soil type of the area (alpine meadow, alpine turf, lithosols and rocks) already reflected variations in slope and aspect.

The third step in hydrologic unit classifications was the consideration of the landforms: strip terraces along the slopes,

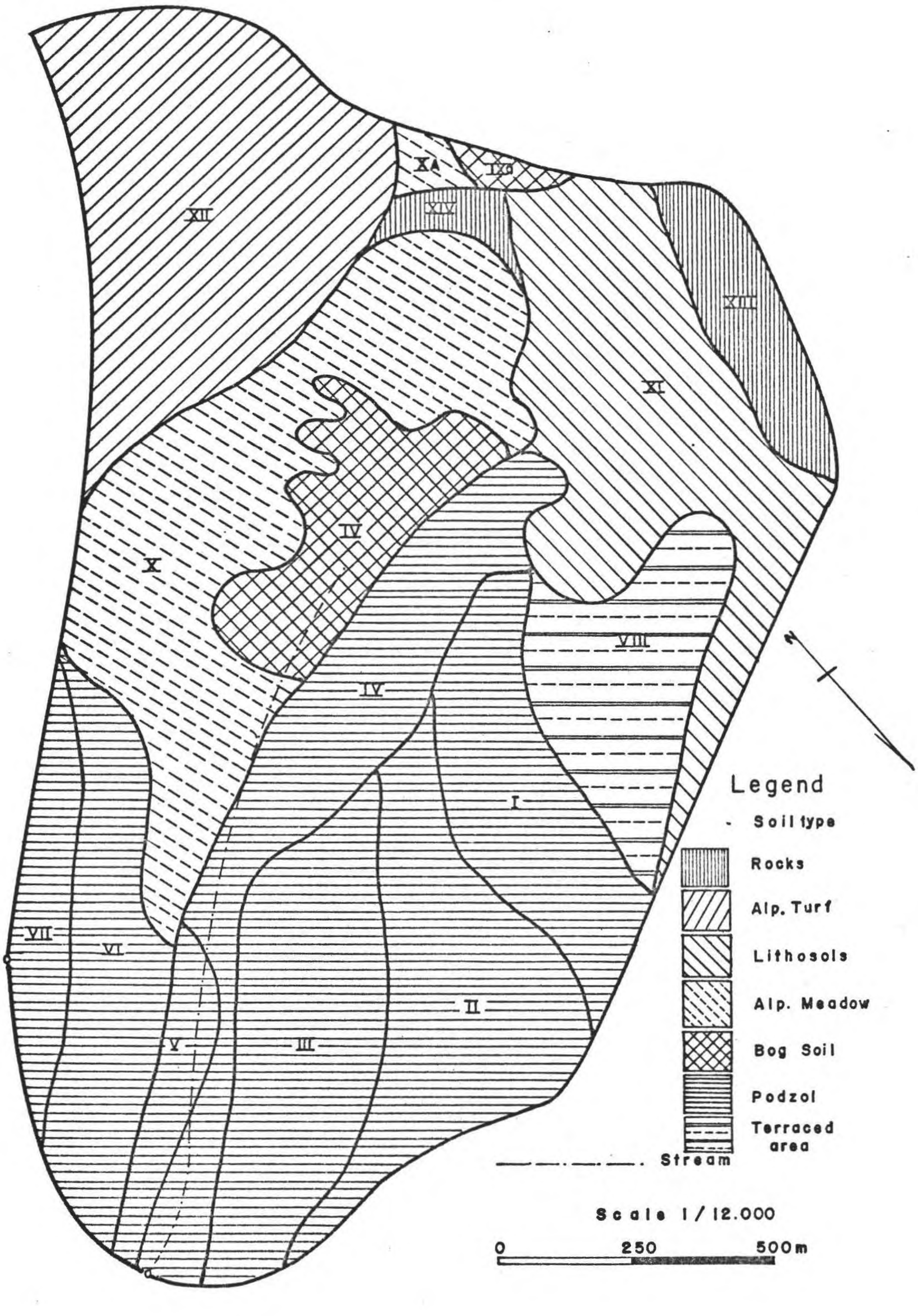

Fig. 36 Hydrologic units and soil types in which they are located.

alluvial terraces along the main stream and the concave area on the central upper part of the watershed.

The location and delineation of the landforms was made directly in the field with aerial photos. A topographic map could have been used, but the only one available had a scale (1/24,000) which was too small for this purpose. As a result, the slope of the strip terraces located on the east-facing side of the watershed, when measured by using the map, averaged 10 to 20%, but measurement in the field showed slopes near 0% on the level part of the terrace and 30 to 40% on the banks which formed them.

The strip terraces located on the east-facing slopes presented a special problem for the classification of the hydrologic units due to the variations in slopes and surface characteristics within very short distances. These small variations could not be reflected in the classification. The strip terraces located on the slopes of Crown Mountain were already included in the previous subdivisions.

The investigations gave the following number of hydrologic units:

Step No. 1 - Soil types = 6 units

Step No. 2 - Slope and aspect = 12 units

Step No. 3 - Landforms = 13 units

The hydrologic and physical characteristics of each unit are presented in Tables C, D, E and F in the appendix. The hydrologic characteristics of each of the classified units were determined based on the hydrologic soil characteristics of the profiles located within their boundaries (Table C). Tables D and E present, respectively, the topographic and vegetation characteristics of each hydrologic unit. The total storage capacity of the watershed to a depth of 1 meter has been

Table 1 Statistical results

	Prediction equation	R	R^2 (%)	S y/x Estimate	Max + deviation (cm water)	Max - deviation (cm water)	Reference (Fig.)
A	$y = 47.5 - 0.74x$	0.73	53.2	8.28	12.4	16.5	35
B	$y = 43.6 - 0.72x$	0.84	71.27	6.49	8.60	9.60	35
C	$y = 51.0 - 0.82x$	0.91	82.95	4.83	6.78	5.37	37
D	$y = 42.3 - 0.65x$	0.91	82.83	4.85	6.3	4.2	37
E	$y = 2.3 - 0.43x$	0.64	41.3	7.31	12.0	13.8	36
F	$y = 19.9 - 0.29x$	0.72	51.5	3.97	6.23	5.36	36

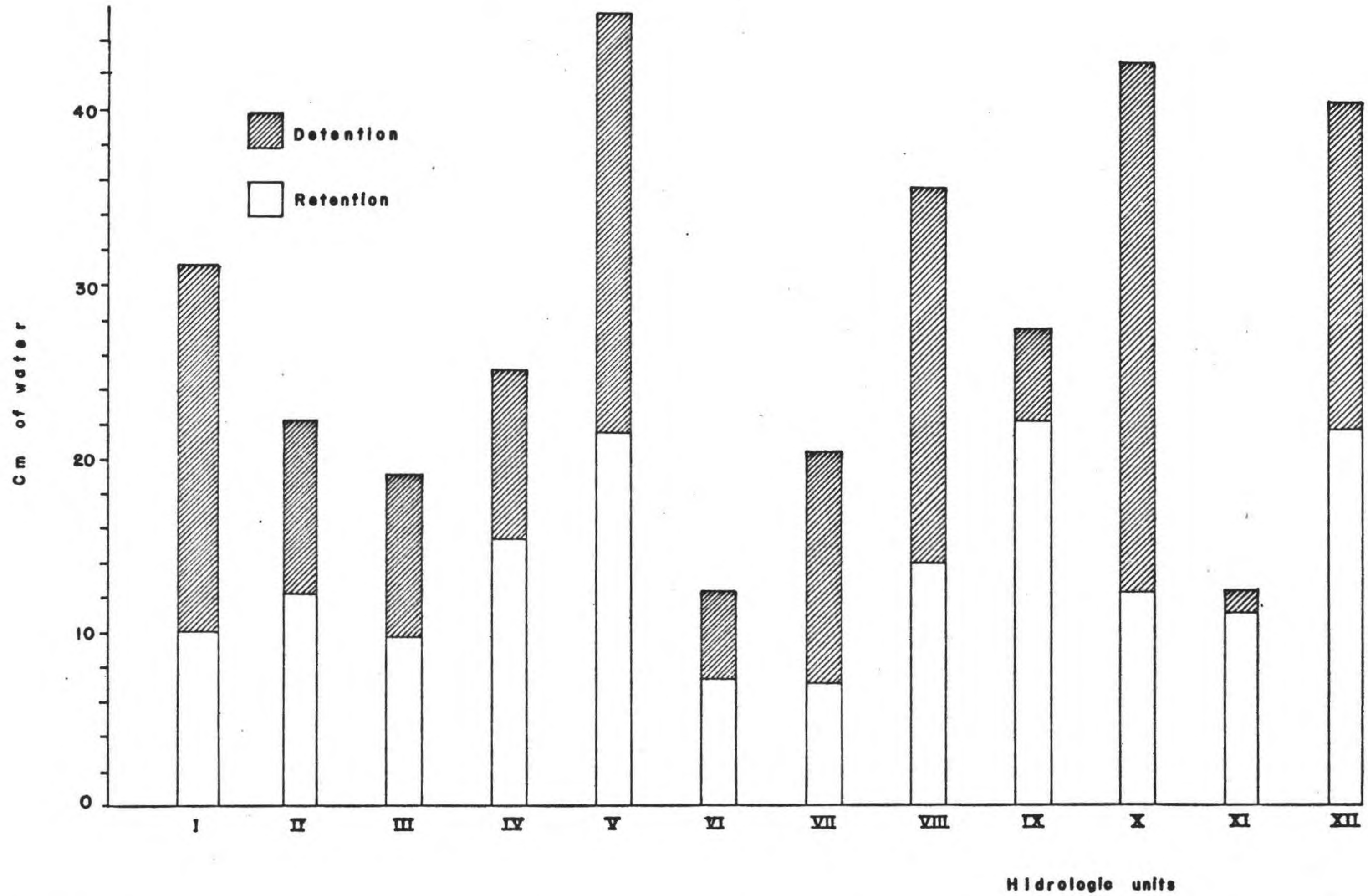

Fig. 37 Retention and detention storage capacities of the surface 1 meter of soil in representative profiles of the hydrologic units.

calculated (Table F) multiplying the area of each hydrologic unit by its respective detention and retention storage capacity.

The considerations to be taken into account with regard to the reliability of these calculations are:

- Many of the units had only one profile which was considered as representative.
- Some of the soil units were very complex. This was most marked on Unit VIII which was formed by strip terraces containing alpine meadow soils alternating with bog soils and lithosols. In this case the only representative profile was located in alpine meadow soils. Unit X located in alpine meadow soils was also represented by one profile which was characterized by a very deep A horizon. The erosion observed in some other zones of the same unit may change the estimated depth of this horizon.
- The limitations of 1 meter of depth affected profiles which had deep horizons with low-bulk density, particularly V and XII located on the alluvial terraces and on alpine turf soils respectively.

The variations in detention and retention storage capacities among the hydrologic units is presented in Fig. 37.

Chapter VI

CONCLUSIONS AND RECOMMENDATIONS

The Upper Little Beaver Watershed has been partitioned into a total of 13 hydrologic units. The hydrologic soil properties considered for the partitioning were hydraulic conductivity, and both water detention and retention storage capacity to a depth of 1 m. The delineation of the boundaries of the hydrologic units was made associating the variations in the hydrologic soil properties with soil types, slope, aspect and landform. It was found that by delineating the boundaries of the major soil types present on the watershed (Podzol, Lithosols, Alpine Meadow, Alpine Turf and Bog Soils) the boundaries of areas with similar hydrologic soil properties were also delineated. However, when variations in slope, aspect and landform existed within the boundaries of a given soil type, further delineation had to be made to take into account the change in hydrologic soil properties caused by these factors. The final delineation gave the boundaries of the classified hydrologic units.

A quantitative analysis was carried out relating some of the hydrologic soil properties to the physical factors of the watershed considered for the separation into hydrologic units. Correlations were made relating values of detention and retention storage capacity; first, with the average slope at the sample site and second, with the slope of the landform at the sample site. The sum of detention and retention storage capacity was defined as total water storage capacity and was used for the correlations. The effect of soil types on the variations in detention and retention storage capacity was evaluated indirectly considering first all the soil types present on the watershed and, second, considering only one soil type. Hydraulic conductivity and aspect were not tested quantitatively due to lack of sufficient data. The following correlations were obtained:

On all soil types:

Average slope versus total water storage capacity
$R = 0.73$ $Sy/x = 8.28$ cm

Landform slope versus total water storage capacity
$R = 0.84$ $Sy/x = 6.49$ cm

Landform slope versus detention storage capacity
$R = 0.64$ $Sy/x = 7.31$ cm

Landform slope versus retention storage capacity
$R = 0.72$ $Sy/x = 3.97$ cm

On one soil type:

Average slope versus total water storage capacity
$R = 0.91$ $Sy/x = 4.83$ cm

Landform slope versus total water storage capacity
$R = 0.91$ $Sy/x = 4.85$ cm

From the study of the hydrologic soil characteristics of the watershed the following average values of hydraulic conductivity and water detention and retention storage capacity were obtained: The hydraulic conductivity of the soils of the watershed was found to be in order of the 67 cm/hr in the upper horizons of podzol and alpine meadow soils, and 16 cm/hr in lithosols and alpine turf soils. The four soil types showed a decrease in their hydraulic conductivity with increase in depth, and all averaged 2 to 3 cm/hr between 50 and 100 cm of depth.

Combined values of retention and detention storage capacity (total water storage capacity) were found to be highest in level areas of the watershed: alluvial terraces, strip terraces and the concave central area. These landforms have an average total water storage capacity of 44 cm of water/100 cm of soil depth. Bog areas also associated with level areas have the highest water retention storage capacity: 22.2 cm of water/100 cm of soil depth. The highest detention storage capacity was found in strip terraces located in alpine turf soils: 31.3 cm of water/100 cm of soil depth. The average total water storage capacity of the watershed was found to be 27.9, the average water retention 13.9, and the average detention 14.2 cm of water/100 cm of soil depth. The total water storage capacity to a depth of 1 m was calculated as $6{,}401 \times 10^2$ m^3 (518.0 acre feet).

It was concluded that the landforms listed above: strip terraces, alluvial terraces and the concave area of the watershed are the most important zones of water storage in the watershed.

The physical factors of the soils which were found to principally affect the hydrologic soil characteristics to a depth of 1 m were: thickness of the different soil horizons, texture, stoniness, structure and bulk density. A coefficient of correlation of 0.89 was found between bulk density and detention storage capacity.

In order to make the results of this research more reliable, it is recommended that it should be extended to other areas in order to obtain more data. Further substantiation would permit wider application of the results obtained.

The conclusions presented here were drawn from a limited amount of data. It is recommended that a compilation of similar data, principally from other watersheds located in the area, be made in order to verify the indicated relationships and permit more sophisticated statistical analyses.

The limitations of 1 meter depth imposed for the storage calculation should be avoided in similar research. The depth of the fractured bedrock should be measured accurately using geological procedures.

A complete hydrogeological study of the area of study should be made. The study of the springs is of capital importance if the watershed is to be used for future hydrological research.

The measurements of hydraulic conductivity using core samples were not adequate due to the high stoniness of the area.

The aerial photos of the area should be compensated in order to be more reliable in the drawing of maps.

Climatic data should be recorded continuously on or close to the watershed.

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LITERATURE CITED

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APPENDIX

APPENDIX A

Table A Profile Description

Profile 1 D

Horizon	Depth (cm)	Description
A_{00}	1-3.5	Undecomposed organic material; needles, bark, twigs, etc.
A_0	3.5-0	Partially and completely decomposed organic material.
A_2	0-5	Gray brown (2.5 Y 5/2 dry) to dark gray brown (2.5 Y 4/2 moist); sandy loam; moderate coarse and fine granular structure; soft dry, friable moist; well aerated; 20% cobbles and stones; moderate to high percolation; lower boundary clear and wavy.
B2ir	5-20	Brown (10 Y 5/3 dry) to dark brown (10 YR 4/3 moist); sandy loam; weak to moderate fine subangular structure; soft dry, friable moist; abundant roots; 30% stoniness; moderate rapid percolation; lower boundary clear.
C	20-75	Yellowish brown (10 YR 5/8 dry) to dark yellowish brown (10 YR 4/4 moist); sandy loam; weak granular structure; hard dry, friable moist; few roots, poor aeration; 40% stoniness; moderate percolation lower boundary gradual.
D	75-100	Yellowish brown (10 YR 5/8 dry) to dark yellowish brown (10 YR 4/4 moist); loamy sand; structureless; no roots; heavily fractured parent material; 80% of stones; slow percolation.

Profile 2 D

Horizon	Depth (cm)	Description
A_1	0-8	Dark gray brown (10 YR 4/2 dry) to very dark gray brown (10 YR 3/4 moist); sandy loam; moderate medium crumb structure; soft dry, friable moist; good aeration; 10% cobbles and stones; moderate to rapid percolation; an abrupt boundary.
A_2	8-25	Gray brown (10 YR 5/2 dry) to very dark gray brown (10 YR 3/2 moist); sandy loam; weak fine crumb structure; soft dry, friable moist; good aeration; 30% angular and flaggy stones; moderate percolation; abrupt boundary.
B_{2ir}	25-50	Light gray (10 YR 6/1 dry) to dark gray (10 YR 4/1 moist); sandy loam; weak medium granular structure; hard dry, loose moist; poor aeration, few roots; 70% cobbles and angular stones; moderate percolation; gradual lower boundary.
C	50-100+	Yellowish brown (10 YR 5/8 dry) to dark yellowish brown (10 YR 4/4 moist); loamy sand; strong coarse and crumb structure; hard dry, loose moist; no roots; 80% angular stones; slow percolation.
A_1	0-5	Dark brown (10 YR 4/3 dry) to very dark brown (10 YR 2/2 moist); sandy loam; moderate fine and crumb structure; soft dry, friable moist; good aeration; 10% cobbles and stones; moderate percolation; abrupt lower boundary.

Profile 3 D

Horizon	Depth (cm)	Description
A_2	5-23	Dark gray brown (10 YR 4/3 dry) to very dark gray brown (10 YR 3/2 moist); sandy loam; moderate fine and crumb structure, soft dry, friable moist; good aeration; 10% cobbles and flaggy stones; moderate percolation; abrupt lower boundary.
B_{2ir}	23-62	Light yellowish brown (10 YR 6/4 dry) to dark yellowish brown (10 YR 4/4 moist); loamy sand; weak coarse and granular structure; slightly hard dry, friable moist; 30% cobbles and flaggy stones; moderate percolation; gradual lower boundary.
C	62-100+	Yellowish brown (10 YR 5/6 dry) to dark yellowish brown (10 YR 4/4 moist); loamy sand; weak coarse and granular structure; very hard dry, friable moist; very poor aeration; 60% angular rocks; slow percolation.

Profile 4 D

A_0		Grasses and hydrophytic plants.
A_1	0-4	Dark brown layer of mixed roots and minerals.
A_2	4-33	Very dark gray brown (10 YR 3/2 dry) to very dark brown (10 YR 2/2 moist); sandy loam; moderate fine and crumb structure; very soft dry, sticky moist; good aeration, high density of roots; 0% stoniness; moderate percolation; abrupt boundary.

Profile 4 D

Horizon	Depth (cm)	Description
AC	33-53	Yellowish brown (10 YR 5/4 dry) to dark yellowish brown (10 YR 4/4 moist); loamy sand; structureless; 40% stones and shoot; no roots; transition layer; rapid percolation; abrupt wavy lower boundary.
C	53-100+	Yellowish brown (10 YR 5/6 dry) to dark yellowish brown (10 YR 4/4 moist); loamy sand; very hard dry, friable moist; poor aeration; 60% cobbles and flaggy stones; slow percolation.

Profile 5 D

Horizon	Depth (cm)	Description
A_2	0-3	Gray (10 YR 7/1 dry) to light brown gray (10 YR 6/2 moist); loamy sand; moderate fine and crumb to granular structure; soft dry, friable moist; good aeration; 50% semi-embedded stones and cobbles; percolation moderate; clear lower boundary.
C_1	3-18	Light yellowish brown (10 YR 6/4 dry) to yellowish brown (7.5 YR 5/8 moist); loamy sand; weak medium and granular structure; soft dry, friable moist; fair aeration; some roots; 20% of cobbles and stones; percolation moderate; diffuse lower boundary.
C_2	18-49	Light yellowish brown (10 YR 6/4 dry) to brownish yellow (10 YR 6/6 moist); loamy sand; weak coarse and granular structure; compacted; 40% cobbles and flaggy stones; some roots at 50 cm; slow percolation; presence of very compacted layer in lower boundary.

Profile 5 D

Horizon	Depth (cm)	Description
C_3	49-80+	Pale brown (10 YR 6/3 dry) to brown (10 YR 5/3 moist); loamy sand; coarse and granular structure; hard dry, loose moist; very poor aeration; slow percolation.

Profile 6 D

Horizon	Depth (cm)	Description
A_1	0-10	Gray brown (10 YR 5/2 dry) to very dark brown (10 YR 2/2 wet); loamy sand, coarse sand and gravel on the first three cm, and sandy loam next 7 cm; moderate fine crumb and granular structure; soft dry; friable moist; very dense net of living roots; 0% stoniness; percolation moderate; clear lower boundary.
A_2	10-47	Dark gray brown (10 YR 4/3 dry) to very dark gray brown (10 YR 3/3 wet); sandy loam; moderate medium and crumb to granular structure; soft dry, friable moist; high density of roots; 0% stoniness; percolation moderate; abrupt lower boundary.
AC	47-67	Dark brown (10 YR 3/3 dry) to dark yellowish brown (10 YR 4/4 moist); coarse sandy loam; weak coarse and granular structure; loose dry, loose moist; transition layer; 10% stones and gravel; good aeration; rapid percolation; gradual and wavy lower boundary.

Profile 6 D

Horizon	Depth (cm)	Description
C	67-100	Yellowish brown (10 YR 5/4 dry) to dark yellowish brown (10 YR 4/4 wet); coarse loamy sand; weak coarse and granular structure; hard dry, loose moist; very compacted; 60% cobbles and subangular and flaggy stones; slow to moderate percolation.

Profile 7 D

A_{00}	4-2	Undecomposed organic material.
A_0	2-0	Decomposed organic material.
A_2	0-12	Dark gray brown (10 YR 4/2 dry) to very dark brown (10 YR 2/2 wet); sandy loam; moderate fine and crumb to granular structure; soft dry, friable moist; high density of roots; 5% stoniness; percolation moderate to rapid; clear lower boundary.
B_{2ir}	12-36	Brown (10 YR 5/3 dry) to dark brown (10 YR 3/3 wet); sandy loam; moderate fine and subangular blocky structure; soft dry; friable moist; fair density of roots, good aeration; 30% cobbles and stones with anuglar, subangular and flaggy shape; moderate percolation; diffuse lower boundary.
C	36-100+	Light yellowish brown (10 YR 6/4 dry) to dark yellowish brown (10 YR 4/4 wet); sandy loam; strong coarse and granular structure; hard dry, loose moist; few roots, poor aeration; 80% stoniness; percolation slow.

Profile 8 D

Horizon	Depth (cm)	Description
A_2	0-25	Dark gray brown (10 YR 3/3 dry) to very dark brown (10 YR 2/2 wet); sandy loam; strong fine crumb structure; soft dry, firm moist; high density of roots, slightly compacted layer; very moist; 20% of flaggy stones; moderate percolation; clear lower boundary.
AC	25-35	Gray brown (10 YR 5/2 dry) to very dark gray brown (10 YR 3/2 moist); sandy loam; slightly strong medium and granular structure; hard dry, loose moist; roots are absent; 10% cobbles and stones; percolation slow to moderate; gradual lower boundary; water table level.
C	35-100	Light yellowish brown (10 YR 6/4 dry) to dark yellowish brown (10 YR 4/4 wet); sandy loam; strong coarse and granular structure; very hard dry, friable moist; no roots; heavily compacted layer; 30% stones with angular and subangular shape; very slow percolation.

Profile 9 D

A_1	0-5	Dark gray (10 YR 4/2 dry) to very dark brown (10 YR 3/2 wet); loamy sand on the surface and sandy loam below; moderate fine and crumb to granular structure; soft dry, friable moist; very high density of roots; slightly compacted layer; 30% cobbles and stones with angular and subangular shape; moderate percolation; abrupt lower boundary.

Profile 9 D

Horizon	Depth (cm)	Description
A_2	5-10	Gray brown (10 YR 5/2 dry) to very dark gray brown (10 YR 3/2 wet); sandy loam; moderate fine and crumb structure; soft dry, friable moist; fair density of roots; 40% of cobbles and angular stones; moderate percolation; clear lower boundary.
B_{2irg}	10-55	Light yellowish brown (10 YR 5/4 dry) to yellowish brown (10 YR 5/4 wet); sandy loam; moderate fine subangular structure; loose dry, loose moist; poor aeration; 40% stones; slow percolation; diffuse boundary.
C	55-120	White (2.5 YR 8/2 dry) to light yellowish brown (2.5 YR 6/4 wet); sandy loam; structureless; fine sand; advanced degree of weathering.

Profile 10 D

Horizon	Depth (cm)	Description
A_0	0-5	Layer with dense net of roots mixed with mineral particles loamy sand.
A_1	5-10	Dark gray brown (10 YR 4/2 dry) to very dark brown (10 YR 2/2 wet); sandy loam; weak coarse crumb to granular structure; soft dry, friable moist; high density of roots; slightly compacted lower; 5% cobbles and stones; moderate percolation; clear lower boundary.

Profile 10 D

Horizon	Depth (cm)	Description
A_2	10-30	Dark yellowish brown (10 YR 4/4 dry) to dark brown (10 YR 3/4 wet); sandy loam; weak to moderate fine subangular blocky structure; soft dry; very friable moist; fair density of roots; good aeration; 20% of stones and cobbles; moderate percolation; clear lower boundary.
B_{2irg}	30-50	Yellowish brown (10 YR 5/4 dry) to dark yellowish brown (10 YR 3/4 wet); sandy loam; moderate fine subangular structure; slightly hard dry, friable moist; poor aeration; 50% of cobbles and angular stones; slow to moderate percolation; clear and wavy lower boundary.
C	50-130+	Olive gray (5 Y 5/2 dry) to dark olive gray; sandy loam; very strong coarse platy structure; advanced degree of weathering; 0% stoniness.

Profile 11 D

A_{00}	4-0	Very thin layer of undecomposed organic material.
A_1	0-5	Very dark layer of decomposed organic matter mixed with minerals; dense net of roots; abrupt boundary
A_2	5-25	Light brown gray (10 YR 6/2 dry) to dark gray brown (10 YR 4/2 wet); sandy loam; moderate medium platy structure breaking to fine crumb; good aeration; 5% cobbles and stones; moderate percolation; clear lower boundary.

Profile 11 D

Horizon	Depth (cm)	Description
B_{2ir}	25-59	Yellowish brown (10 YR 5/4 dry) to dark yellowish brown (10 YR 4/2 wet); sandy loam; moderate medium coarse subangular blocky structure; slightly hard dry; firm moist; 20% cobbles and stones; moderate percolation; gradual lower boundary.
C	59-100	Yellowish brown (10 YR 5/6 dry) to dark yellowish brown (10 YR 4/4 moist); sandy loam; granular structure; very hard dry, loose moist; highly compacted; 50% stones and cobbles; slow percolation.

Profile 12 D

Horizon	Depth (cm)	Description
A_{00}	6-5	Undecomposed organic material.
A_0	5-0	Partially and completely decomposed organic matter.
A_2	0-21	Light brown gray (10 YR 6/2 dry) to dark brown (10 YR 3/3 moist); loam; moderate fine crumb structure; soft dry, friable moist; high density of roots; 10% of cobbles and stones; moderate percolation; clear lower boundary.
B_{2ir}	21-80	Dark gray brown (10 YR 4/2 dry) to dark brown (10 YR 3/3 moist; sandy loam; moderate medium granular structure; hard dry, friable moist; few roots; 40% cobbles and stones; moderate percolation; clear lower boundary.
C	80-100	Light olive brown (2.5 Y 5/4 dry) to olive brown (2.5 Y 4/4 wet); sandy loam; weak fine granular structure; soft dry, loose moist; few roots; 0% stones; moderate percolation; diffuse lower boundary with increasing stoniness.

APPENDIX B

Table B

Prof.	Depth		Stoniness %	Sand	Silt	Clay			1/10	1/3	15
1	0- 35	A	-	-	-	-	-	-	-	40.1	25.2
	0- 5	A_2	20	65.6	28.2	6.2	sandy	loam	35.6	27.7	6.4
	5- 20	B_{2ir}	30	61.6	26.8	11.6	sandy	loam	25.7	21.2	5.6
	20- 72	C	40	71.2	19.6	9.2	sandy	loam	20.7	10.7	4.9
	72-100	D	80	75.0	16.2	8.8	loamy	sand	18.5	14.5	5.8
2	0- 8	A_1	10	59.2	30.6	10.2	sandy	loam	38.5	32.1	10.3
	8- 25	A_2	30	62.0	23.8	14.2	sandy	loam	23.2	19.1	7.7
	25- 50	B_{2ir}	70	75.2	15.6	9.2	sandy	loam	13.7	9.4	3.3
	50-100	C	80	78.2	12.6	9.2	loamy	sand	13.8	9.2	4.6
3	0- 5	A_1	10	70.0	25.2	4.8	sandy	loam	32.0	21.0	14.45
	5- 23	A_2	10	71.0	22.2	6.8	sandy	loam	26.3	17.2	9.3
	23- 62	B_{2ir}	30	78.8	10.4	10.8	loamy	sand	15.0	9.4	4.0
	62-100	C	60	79.6	12.4	8.0	loamy	sand	28.3	12.3	5.9
4	0- 4	A_1	0	78.8	14.8	6.4	loamy	sand	71.9	41.7	15.57
	4- 33	A_2	0	71.2	21.2	7.6	sandy	loam	26.8	21.3	9.56
	33- 53	AC	40	82.6	9.0	8.4	loamy	sand	21.5	15.6	3.99
	53-100	C	60	80.0	9.6	10.4	loamy	sand	15.0	12.8	5.79
5	0- 3	A_2	50	71.2	22.4	6.4	sandy	loam	23.4	18.7	10.16
	3- 18	C_1	20	74.8	17.6	7.60	loamy	sand	17.4	13.7	2.2
	18- 49	C_2	40	84.8	12.8	5.4	loamy	sand	14.9	9.4	2.0
	49-100	C_3	80	84.0	9.6	6.4	loamy	sand	13.4	11.9	2.5

Table B (continued)

Prof.	Depth		Stoniness %	Sand	Silt	Clay		1/10	1/3	15
6	0- 10	A_1	0	79.0	12.2	8.8	loamy sand	16.5	11.5	6.7
	10- 47	A_2	0	72.8	18.6	8.6	sandy loam	23.2	15.1	7.0
	47- 67	AC	10	79.2	10.8	10.0	loamy sand	16.2	11.2	3.4
	67-100	C	60	84.8	8.8	6.4	loamy sand	10.3	8.4	3.2
7	0- 4	A_{00},A_0	0	organic matter			- -	-	95.5	40.6
	0- 12	A_2	5	70.8	22.4	6.8	sandy loam	31.0	23.2	10.2
	12- 36	B_{2ir}	30	58.8	26.8	14.4	sandy loam	31.1	23.5	7.5
	36-100	C	80	68.4	18.8	12.8	sandy loam	19.5	13.5	4.3
8	0- 25	A_2	20	56.0	39.6	4.4	sandy loam	65.0	44.6	21.4
	25- 35	AC	10	62.0	24.0	14.0	sandy loam	31.0	25.1	8.7
	35-100	C	30	70.6	15.2	14.2	sandy loam	22.6	11.0	3.3
9	0- 5	A_1-A_3	5	76.7	15.2	7.1	loamy sand	-	39.2	28.0
	5- 30	A_3-B_{2irg}	20	65.6	26.8	7.6	sandy loam	30.5	21.4	8.8
	30- 55	B_{2irg}-C	40	70.1	23.2	16.7	sandy loam	45.6	28.9	10.4
	55-100	C	0	71.2	16.8	12.0	sandy loam	26.4	22.2	8.0
10	0- 5	A_1	10	79.6	13.0	7.4	loamy sand	-	41.2	30.1
	5- 10	A_2	10	71.2	22.4	6.4	sandy loam	34.7	21.8	13.2
	10- 30	A_2	30	64.6	27.8	7.6	sandy loam	31.7	25.9	12.6
	30- 50	B_{2ir}	50	71.4	15.2	13.4	sandy loam	29.7	27.9	12.5
	50- 90	C	0	78.4	13.20	6.8	sandy loam	18.7	16.7	7.6
	90-100	C	0	83.2	13.20	3.60	sandy loam	21.6	12.5	5.5
11	0- 5	A_1	-	-	-	-	- -	-	42.1	21.6
	5- 25	A_2	5	64.4	26.2	9.4	sandy loam	21.0	10.8	5.2
	25- 59	B_{2ir}	20	63.1	21.6	15.2	sandy loam	19.0	13.8	6.9
	59-100	C	50	65.6	17.6	6.8	sandy loam	7.6	5.2	2.5

Table B (continued)

Prof.	Depth		Stoniness %	Sand	Silt	Clay			1/10	1/3	15
12	0- 5	A_0	-	-	-	-	-	-	-	-	-
	0- 21	A_2	10	39.2	42.4	18.4	loam		36.6	28.7	7.34
	21- 80	B_{2ir}	40	57.2	29.2	13.6	sandy	loam	29.6	21.9	7.2
	80-100	C	0	70.4	20.2	26.6	sandy	loam	23.3	19.9	3.8
	100	C	70	78.4	16.4	5.2	sandy	loam	28.6	17.8	6.3
2K	0- 1		5	54	36	10	sandy	loam	48.3	31.0	16.9
	1- 12		5	58	29	13	sandy	loam	31.4	25.0	9.6
	12- 33		20	67	20	13	sandy	loam	20.5	15.0	4.7
	33-100		50	68	22	10	sandy	loam	45.0	10.0	4.6
6K	0-3.5		0	-	-	-	5	-	-	53.1	19.2
	0- 9		20	58	29	13	sandy	loam	21.8	16.0	4.7
	9- 36		65	65	23	12	sandy	loam	19.0	14.5	7.6
	36-100		80	72	21	7	sandy	loam	17.2	12.0	6.3

APPENDIX C

Table C

Hy. unit	Pro.	Depth cm	Bulk den. g/cm^3	Por. vol. %	0.33 bar vol. %	15 bar vol. %	vol. %	Det. cm	Ret. cm	W.a.p. cm	Perc. cm/hr.
I	3D	0- 5	0.79	70.3	76.6	11.41	53.7	2.4	0.8	0.2	14.0
		5- 23	0.85	67.9	14.7	7.9	53.2	8.6	2.4	2.4	35.0
		23- 62	1.50	43.6	14.1	6.0	29.5	8.1	3.9	3.9	12.9
		62-100	1.74	34.4	21.3	10.3	13.1	2.0	3.2	3.2	2.0
								21.1	10.3	9.7	
II	2K	0- 1	1.0	62.3	31.0	16.9	31.3	0.3	0.3	0.1	
		1- 12	1.10	58.5	27.5	10.5	31.0	3.3	3.1	2.1	
		12- 33	1.49	42.8	22.3	7.0	20.5	3.3	3.5	2.3	
		33-100	1.65	27.0	16.5	7.6	10.5	3.5	5.5	3.0	
								10.4	12.4	7.5	
	1D	3.5-0	0.50	58.4	25.0	12.6	38.4	1.3	0.7	0.6	
		0- 5	0.90	66.0	2.9	5.8	41.1	1.6	1.0	0.8	59.0
		5- 20	1.54	41.8	32.7	8.6	9.1	1.0	3.4	0.8	41.2
		20- 72	1.85	30.2	19.8	5.2	10.4	5.4	5.7	4.0	15.0
		72-100	1.90	28.1	26.8	10.7	1.3	0.1	1.5	0.9	

Table C (continued)

Hy. unit	Pro.	Depth cm	Bulk den. g/cm^3	Por. vol. %	0.33 bar vol. %	15 bar vol. %	satur.	Det. cm	Ret. cm	W.a.p. cm	Perc. cm/hr.
III	2D	0- 8	0.96	62.7	30.9	9.9	31.8	2.2	2.2	1.5	
		8- 25	1.30	51.1	24.7	10.1	26.4	3.2	3.0	1.8	
		25- 50	1.62	38.9	16.0	5.6	22.9	1.7	2.0	1.3	
		50-100	1.85	30.2	17.0	8.51	13.2	1.7	2.0	1.2	
								9.8	9.2	5.8	
IV	7D	2- 0	0.40	53.0	23.3	13.2	30.4	0.6	0.3	0.1	
		0- 12	1.14	56.9	26.5	11.7	30.4	3.4	3.0	1.7	
		12- 36	1.23	53.4	29.1	9.3	24.3	4.1	5.9	4.4	
		36-100	1.85	30.2	24.9	7.8	05.3	1.4	6.4	4.4	
								9.5	15.5	10.6	
V	12D	5- 0	0.35	77	22.0	10.1	55.1	2.7	1.1	1.6	
		0- 21	0.97	63.3	27.9	7.12	35.4	6.7	5.3	4.1	
		21- 80	1.26	52.5	27.6	9.10	24.9	8.8	9.7	2.1	
		80-100	1.34	49.4	26.6	5.1	22.8	6.0	5.3	1.0	

Table C (continued)

Hy. unit	Pro.	Depth cm	Bulk den. g/cm^3	Por. vol. %	0.33 bar vol. %	15 bar vol. %	satur.	Det. cm	Ret. cm	W.a.p. cm	Perc. cm/hr.
VI	6K	3.5-0	0.42	65	22.3	8.0	42.7	1.5	0.8	1.2	
		0- 9	1.19	55.1	19.0	5.6	36.1	2.6	1.4	1.0	
		9- 36	1.78	32.9	25.8	13.5	07.1	0.7	2.4	1.1	
		36-100	1.80	22.1	21.6	11.3	10.3	0.1	2.8	1.3	
								4.9	7.4	4.6	
VII	11D	4-0	0.53	56	22.3	11.45	33.7	1.3	0.9	0.4	
		0- 25	1.10	58.5	16.3	5.7	42.2	5.9	2.3	1.5	
		25- 59	1.40	48.0	19.1	9.7	28.9	4.2	2.6	1.3	
		59-100	1.90	28.0	9.9	4.7	18.1	1.5	1.5	0.4	
								12.9	7.3	3.6	
VIII	4D	0- 4	0.73	72.3	30.0	11.36	42.3	1.2	1.7	0.8	67.3
		4- 33	1.03	61.1	21.9	9.8	39.2	11.4	6.3	3.5	28.9
		33- 53	1.11	58.1	17.3	4.4	40.8	4.9	2.2	0.5	14.5
		53-100	1.53	42.2	20.0	8.8	22.2	4.0	3.8	1.5	3.1

Table C (continued)

Hy. unit	Pro.	Depth cm	Bulk den. g/cm^3	Por. vol. %	0.33 bar vol. %	15 bar vol. %	satur.	Det. cm	Ret. cm	W.a.p. cm	Perc. cm/hr.
IX	8D	0- 25	1.02	61.5	45.5	21.8	16.0	3.2	9.1	4.8	
		25- 35	1.25	52.7	31.6	10.9	21.1	1.9	2.9	1.9	
		35-100	2.03	23.1	22.5	6.7	0.6	0.3	10.2	7.2	
								5.4	22.2	13.9	
X	6D	0- 10	0.99	62.7	11.4	6.6	51.3	05.1	1.1	0.4	
		10- 47	1.12	57.5	17.0	7.8	50.5	18.7	6.3	3.4	
		47- 67	1.36	48.7	15.3	4.6	33.4	06.0	2.8	2.0	
		67-100	1.92	27.6	16.1	1.1	11.5	01.5	2.1	1.3	
								31.3	12.3	7.1	
XI	5D	0- 3	1.01	6.19	18.9	10.3	51.6	0.4	0.7	0.2	16.2
		3- 18	1.70	25.2	23.3	3.7	1.9	0.2	0.8	2.4	6.8
		18- 49	1.95	26.6	25.1	3.9	1.5	0.4	4.7	4.0	1.5
		49-100	1.98	25.3	23.7	4.9	1.6	0.2	3.0	2.5	
								1.2	11.2	9.1	

Table C (continued)

Hy. unit	Pro.	Depth cm	Bulk den. g/cm^3	Por. vol. %	0.33 bar vol. %	15 bar vol. %	satur.	Det. cm	Ret. cm	W.a.p. cm	Perc. cm/hr.
XII	9D	0- 5	0.60	50.0	23.5	16.8	26.5	1.2	1.3	0.1	
		5- 10	1.18	55.4	25.3	10.4	30.1	.2	1.1	0.7	
		10- 55	1.17	55.9	33.8	12.2	22.1	4.9	7.6	2.2	
		55-100	1.32	50.1	29.4	10.6	20.7	9.3	13.2	8.5	
								16.6	23.2	11.5	
	10D	0- 5	0.57	53	23.5	17.1	29.5	1.4	1.3	0.1	
		5- 10	1.04	60.8	22.7	13.7	38.1	1.7	1.0	0.4	15.5
		10- 30	1.17	55.7	30.4	14.7	25.3	3.6	4.3	0.4	10.2
		30- 50	1.16	56.3	32.3	14.5	24.0	2.4	3.2	1.8	5.7
		50- 90	1.35	49.1	22.6	10.2	26.5	10.6	9.0	4.9	7.9
		90-100	1.46	44.9	18.2	08.0	26.7	2.7	1.8	1.0	2.6
								22.4	20.6	8.6	
								19.5	21.9	10.0	

APPENDIX D

Table D

Unit	Area (Has)	Area (%)	Aspect	Average slope (%)	Landform slope (%)	Character. slope	Character. landform	Soil type
I	14.8	6.5	E	15-25	15	Strip	Terraces	Podz.
II	17.6	7.5	E	30-40	25	Even	Convex	Podz.
III	19.4	8.4	E	40-50	45	Even	Straight	Podz.
IV	19.9	8.5	E	20-30	20	Uneven	Concave	Podz.
V	4.5	1.8	N	10-20	5	Alluv.	Terraces	Podz.
VI	14.0	6.0	N	40-50	45	Even	Straight	Podz.
VII	6.3	3.0	N	30-40	30	Convex	Ridge	Podz.
VIII	11.8	5.5	E	10-20	10	Strip	Terraces	Bog-Podz.
IX	10.6	5.0	N	10-20	10	Concave	Area	Bog Soil
IXa	1.0	0.5	N	10-20	10	Concave	Area	Bog Soil
X	37.3	15.9	N	10-20	10	Concave	Area	Alpine Meadow
Xa	1.0	0.5	N	10-20	10	Concave	Area	Alpine Meadow
XI	30.2	12.9	E	20-30	30	Even	Convex	Lithosols
XII	33.8	14.0	NE	20-30	15	Strip	Terraces	Alpi. Turf
XIII	6.8	3.0	E	10-20	15	Ridge	Convex	Rocks
XIV	1.9	1.0	N	40-50	45	Talus	Rocks	Rocks

APPENDIX E

Table E

Unit	Shrubs	Grass herbs	Mosses	Litter	Bare soil	Surface rocks	Total	Canopy cover
I	15	20	-	15	20	30	100	30
II	5	30	-	25	10	30	100	25
III	5	30	-	40	10	15	100	20
IVa	r	20	5	70	-	5	100	50
IVb	r	20	5	60	-			
V	r	5	10	65	5	15	100	10
VI	r	15	r	50	20	15	100	10
VII	40	20	-	15	15	20	100	15
VIII	60	15	-	-	15	10	100	2
VIIIa	60	15	-	-	15	10		-
IX	20	50	-	-	20	10	100	-
IXa	20	50	-	-	20	10	100	-
X	35	10	-	-	10	45	100	
XI	25	30	-	-	20	15	100	5
XII	-	5	-	-	5	90	100	0
XIII	-	-	-	-	-	100	100	0

APPENDIX F

Table F

Unit	Area	Detent.	Retent.	Wat. a.p.	Total detent.	Total retent.	Total wat. a.p.
	(Has)	(cm)	(cm)	(cm)			
I	14.8	21.1	10.3	9.7	312.3	152.4	143.5
II	17.6	9.9	12.3	7.8	174.0	216.5	137.4
III	19.4	9.8	9.2	5.8	184.3	178.5	112.5
IV	19.9	9.5	15.5	10.6	189.0	308.4	210.9
V	4.5	24.0	21.4	8.8	108.0	96.3	39.6
VI	14.0	4.9	7.4	4.6	68.6	103.6	64.4
VII	6.3	12.9	7.3	3.6	81.3	46.0	22.8
VIII	11.8	21.5	14.0	6.3	253.7	165.2	74.3
IX	10.6	5.4	22.2	13.9	57.2	235.2	147.3
IXa	1.0	5.4	22.2	13.9	5.4	22.2	13.9
X	37.3	31.3	12.3	7.1	1,165.5	458.8	264.8
Xa	1.0	31.3	12.3	7.1	31.3	12.3	7.1
XI	30.2	1.2	11.2	9.1	36.2	338.2	274.8
XII	33.8	19.5	21.9	10.0	659.1	740.2	338.0
XIII	6.8	-	-	-	-	-	-
XIV	1.9	-	-	-	-	-	-
			Total	m^3 10^2 -	3,327.9	3,073.8	1,851.2
				ac-ft	269.0	249.0	149.9