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Title HYDROLOGIC SIGNIFICANCE OF THE GRANITIC PARENT MATERIAL OF THE SAN GABRIEL MOUNTAINS, CALIFORNIA

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The study was conducted on the San Dimas Experimental Forest in southern California. It deals with a field and laboratory evaluation of several physical and hydraulic properties of the weathered parent material and suggests how these properties may relate to flood runoff problems.

A simple correlation analysis shows that only one variable, non-capillary porosity had a significant relationship with saturated hydraulic conductivity. A factor analysis indicated that information from 19 descriptive variables could be attributed to 5 common factors. The 5 common factors show the types of variables that would be most useful in describing parent material.

Darcy's equation was used to compute saturated hydraulic conductivity. The resulting computations, utilizing Reynolds number criterion, yielded values which were well within the laminar flow range. However, differing Reynolds numbers were obtained by using average grain size as compared to average pore diameters.

A comparison between field hydraulic conductivity and laboratory hydraulic conductivity showed no significant correlation between the two measurements.

Moisture-retention curves of the surface and parent material show little difference between the two materials. Retention and detention storage values for the soil and parent material were calculated and used to assess the occurrence of overland flow.

The importance of the parent material, as it influences overland flow, was evaluated utilizing existing rainfall records, streamflow hydrographs, moisture storage values and the permeability results of this study. Total storm and 24-hour rainfall data were not very useful for evaluating the presence or absence of overland flow. Rainfall was budgeted into the soil and parent material according to the respective permeabilities and storage capacities of those two strata. Overland flow was computed by subtracting the amount of water infiltered from the amount of rain falling during a six minute time period. Rainfall hyetographs and streamflow hydrographs indicated that overland flow is of limited occurrence even during flood runoff periods. Flood peaks were thought to be the result of storm seepage flow from the side slopes rather than from direct channel interception or overland flow.

Any overland flow coming from recently burned watersheds probably results from a change in the soils permeability characteristics. The soil resists wetting because of a water repellency created by wildfire temperatures.

HYDROLOGIC SIGNIFICANCE OF THE GRANITIC PARENT MATERIAL OF THE SAN GABRIEL MOUNTAINS, CALIFORNIA

by

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HYDROLOGIC SIGNIFICANCE OF THE GRANITIC PARENT MATERIAL OF THE SAN GABRIEL MOUNTAINS, CALIFORNIA

INTRODUCTION

Purpose

The U. S. Forest Service has been conducting extensive studies on surface hydrology problems at the San Dimas Experimental Forest in southern California. The broad research objectives are to determine how watersheds function and to develop sound watershed management practices for the protection of the urban population of the Los Angeles River basin.

A major part of the past research program has been aimed at water yield improvement. Flood runoff studies have dealt primarily with post-fire periods. There have been no quantitative studies from the Experimental Forest indicating to what extent the granitic parent material may influence surface runoff.

The physical properties of a particular profile usually determines its permeability. The location of the least permeable layer has the deciding influence on subsequent surface or subsurface runoff. Sometimes the parent material is the controlling strata.

A granitic parent material underlies almost 50 percent of the thin soils of the San Gabriel Mountain range. It is hypothesized that this important rock type has a considerable capacity to transmit and temporarily store water during periods of flood runoff. Therefore, it is important to understand what role the granitic parent material has in the hydrology of the San Gabriel Mountain watersheds.

The purpose of this study was to investigate the hydraulic properties of the weathered granitic parent material and determine how those properties relate to the flood hydrology of the area. Measurements of the physical properties of the parent material were made in order to determine; first, some basic information about the parent material and second, the relationship between the physical and hydraulic properties as they relate to the hydrology of the mountain watersheds.

Scope

The decomposed granitic parent material samples were taken from the Tanbark Flat area on the San Dimas Experimental Forest. Study sites were confined to recently constructed contour trenches. Samples were taken from depths up to 6 feet below the soil surface.

The rainfall, runoff, and soil moisture data that were utilized were obtained from existing sources. An assumption of the study was that the hydraulic properties of the granitic parent material could be described by the field and laboratory measurements of this study. The new field and laboratory measurements include only those of porosity, bulk density, particle density, moisture-retention characteristics, pore size distribution, depth from the soil surface, mineral composition, particle size distribution, field infiltration, and hydraulic conductivity. Darcy's equation was used to calculate all hydraulic conductivity values.

REVIEW OF LITERATURE

The literature cited includes papers considered most pertinent to the subject and at the same time tries to be representative of the large body of literature available.

This study was concerned with the measurement and use of the variable termed hydraulic conductivity, defined as the ratio of the flow velocity to the driving force for the viscous flow under saturated conditions of a specified liquid in a porous medium (Soil Science Society of America, 1965). Permeability, as used in describing soils, refers to the property of a porous medium itself that relates to the ease with which gases, liquids, or other substances can pass through it (Soil Science Society of America, 1965). Hydraulic conductivity and permeability are synonymous throughout the literature review and this study. Infiltration refers to the downward entry of water into the soil. The infiltration rate is a soil characteristic determining or describing the maximum rate at which water can enter the soil under specified conditions, including the presence of an excess of water (Soil Science Society of America, 1965). The term infiltration cannot be substituted directly for hydraulic conductivity or permeability unless the soil is fully saturated. It is inferred that infiltration rate has some relationship to hydraulic conductivity in that an infiltration rate must be known in order to compute the soils hydraulic conductivity.

Physical Properties Affecting Saturated Moisture Movement

Morris and Johnson (1967) list the physical properties of soils and rock materials as analyzed by the U. S. Geological Survey's Hydrologic Laboratory as: permeability, unit weight, specific gravity, total porosity, effective porosity, centrifuge moisture equivalent, specific retention, specific yield, Atterberg limits and indices, particle size distribution, moisture content, degree of saturation, and pore size distribution. The first ten measurements are the most commonly requested by the Geological Survey's research scientists for use in permeability studies.

Properties of Water

Fletcher (1949) measured several properties of water that influence permeability and gave brief experimental evidence to support his conclusions. He concluded that infiltration increases linearly with surface tension, decreases hyperbolically with viscosity, increases parabolically with pore size, increases in a skewed cosine curve with wettability, and increases linearly with temperature. Not considered, however, are the interactions of the variables to the overall relationship of water movement. The separation of viscosity from temperature does not seem justified even if different curves are produced since viscosity is temperature dependent. Earlier Moore (1940) reported that gross trends of his infiltration curves indicated effects due to viscosity of the water solution. Lewis (1937) and Lewis and Powers (1938), studying the factors affecting permeability concluded that pore characteristics, hydraulic gradient and viscosity of the fluid were all related to flow rates through the porous media.

Hydraulic Head

Arvonovici (1955) found that between heads of 2.5 and 11 centimeters of water there were significant increases in water movement. The variation in rate was due to water moving into initially dry soils. Lewis and Powers (1938) found little difference between 1 inch and 3 foot heads. The small difference in infiltration using a 1 inch and 3 foot head appears to result from a sealing of the soil at the surface. Philip (1958) in his study found that infiltration increases only slightly as head increases. He states further that the effect of depth of water above the surface on infiltration rate decreases gradually with time and ultimately becomes zero as time approaches infinity. However, Philip's work is based primarily on theoretical calculations of water movement into a uniform soil system. Philip (1958) states that it is likely that experiments indicating definite effects of head on the "long-time" rate have been made on nonuniform soils where effects of a hydraulic head are quite possible.

Schiff (1953) observed that an increase in infiltration rate was directly proportional to the head of water imposed on the surface.

Not stated are the other factors, such as antecedent moisture or entrapped air, which also affect water movement. Bodman and Colman (1943) observed that saturation was only obtained in the first few centimeters below the surface and below this the moisture content dropped to 80 percent of saturation. The same phenomenon was observed by Lambe (1951) in experiments of horizontal water movement. The relatively shallow saturated moisture fronts in the fine textured soils studied by Bodman and Colman and Lambe appeared to result from air being entrapped in the larger pores. A study by Youngs (1957) shows the saturated moisture profile to be constant with depth. The moisture fronts produced during infiltration under laboratory conditions imposed by Youngs allowed very few of the larger pores to be cut off by surrounding smaller pores filling first and resulting in less entrapped air than reported by Bodman and Colman.

Porosity

The seemingly important porosity variables are total and non-capillary porosity. Total porosity is defined as the volume percentage of the total bulk not occupied by solid particles. Non-capillary porosity is the proportion of the bulk volume of soil that is filled with air at any given time or under a given condition such as a specified moisture tension. Usually the large pores; that is, those drained by a tension of less than approximately 100 centimeters of water are defined as the non-capillary pores (Soil Science Society of America, 1965).

Baver (1956) presents information on sand, zeolite, clays, and soils in their natural structure and shows a highly significant relationship between hydraulic conductivity and non-capillary porosities of the material. In a different study on a number of soils Nelson and Baver (1940) found a tension of 40 centimeters (water) gave the best relationship between hydraulic conductivity and non-capillary porosity. Tensions ranging from 10 centimeters to 180 centimeters were used in their study.

Bendixen and Salter (1947) showed that there was a time factor present during tension measurements for determining non-capillary porosity. They contended that drainage at tensions greater than 40 centimeters of water may contribute greatly to the rate of water movement. They found the best results for non-capillary porosity by using a drainage period of 1 hour at 60 centimeters of tension. Peele (1949), using soil cores and both 15 and 30 minute time periods at 60 centimeters suction, found a significant correlation between the volume of pores drained and the percolation rate.

Bodman (1936) has shown that textural differences exert little influence on hydraulic conductivity at very high bulk density for soils finer than fine sandy loams. He showed that the percolation was exceedingly slow at bulk densities greater than 1.4 to 1.5 grams per cubic centimeter but also stated that a decrease in total porosity was not always the reason for reduced hydraulic conductivity. Bodman concluded that the most important permeability variable appears to be the distribution of large pores in the soil system. It is recognized that these results are empirical. However, they emphasize the importance of non-capillary porosity in studies of the movement of water through the soil system.

Whipkey (1966) pinpoints large soil channels where roots formerly existed and earthworm holes as the paths which carried most of the observed stormflow in the fine textured forest soils. Those factors are rarely measured as a physical property affecting permeability but appear to have considerable influence on flow rates under natural conditions.

A measurement termed specific yield is commonly used in groundwater literature and is synonymous with non-capillary porosity as used in the soils literature.

Specific yield is defined as the ratio of water which can be drained freely from a rock or soil to the total volume of water held by the material (Linsley, Kohler, and Paulhus, 1959). Specific yield is always less than porosity. The specific yield of subsoils is a variable considered to be important for quantitative estimates of permeability. Perrier and Johnson (1963) measured specific yield from disturbed core samples within a fairly rapid period of time with highly reproducible results. The results indicated that it was possible to predict specific yield from mechanical analysis data and 15 atmosphere moisture content.

Pore-Size Distribution

Pore-size distribution is defined as the volume of the various sizes of pores in the soil and expressed as a percentage of the bulk volume (Soil Science Society of America, 1965).

Childs and Collis-George (1950) contend that pore size distribution as measured from moisture-suction characteristics of a material is a better measure of permeability than a formula such as the Darcy equation. To support this idea, they developed a statistical theory based on the calculation of the probability of occurrence of sequences of pairs of pores of all possible sizes, and from the contribution to the permeability made by each pair, developed an expression of the permeability from the sum of a series of mathematical terms. From these calculations, permeability can be computed for any desired moisture content. The theory checked well with 2 grades of sand and 1 sample of slate dust. Marshall (1958) developed a procedure using the statistical approach of Childs and Collis-George and Poiseuille's equation that could be used to predict saturated hydraulic conductivity without the determination of an empirical constant. The Marshall formula can be expressed in terms of the tension required to remove water as follows:

$$Km = \frac{E^2 s^2}{2d\ g\ \eta\ n^2}\left[\frac{1}{h_1^2} + \frac{3}{h_2^2} + \frac{5}{h_3^2} + \ldots\ldots + \frac{2(n-1)}{h_n^2}\right]$$

in which

Km = hydraulic conductivity in centimeters per hour

E = porosity

s = surface tension in dynes per centimeter

d = density of fluid in grams per cubic centimeter

g = acceleration of gravity in centimeters per second squared

n = number of arbitrary divisions into which E is divided

h_i = tension of fluid in centimeters per i^{th} division of tension

η = viscosity of the fluid in poises

Marshall tested the Childs and Collis-George equation on existing published data. Calculated values of permeability were found to agree satisfactorily with measured values over a wide range of permeabilities. Schmidt (1963) used the technique developed by Marshall (1958) to calculate changes in porosity with increased levels of soil compaction. There was good agreement in the reduced permeabilities as predicted from the pore size distribution. These studies emphasize the importance of a moisture tension curve for determining permeability and the significance to moisture movement.

Particle Size Distribution

Wenzel (1942) used a uniformity coefficient to indicate the particle size distribution of an aquifer. The uniformity coefficient is defined as the ratio of the 60 percent grain diameter (diameter for which 60 percent of the particles, by weight, are finer) to the 10 percent grain diameter (Meinzer, 1942). A small uniformity coefficient denoted by a steeply sloping particle size curve, indicates a uniformly graded mixture. A large coefficient with a flat curve denotes a well graded mixture. Norris and Fidler (1965) using uniformity coefficients established from particle size distribution curves concluded that the uniformity coefficients of the material gave reasonably good indices of their respective permeabilities. The Johnson Company (1959) states that, "Many attempts have been made to calculate the permeability from results of grain size tests of sand samples from sand analysis. Some success has been obtained in dealing with formation materials in a given locality. However, no formula has yet been devised that will give reasonably accurate values for permeability that can be applied to a wide range of sand types". The quotation contradicts the volumes of literature that have used an empirical formula for such purposes.

Studies of the permeability and specific yield of porous media by Johnson (1964) used the variables of entrapped air, particle size distribution, porosity and hydraulic gradient. A good correlation was developed between the permeability and particle size if both particle size distribution and dominant particle size are treated statistically.

Mineralogic Composition

Johnson and Sherman (1950), Goldich (1938), Jenny (1941), and Wilde (1958) cover the general aspects of parent material weathering to form soil. Keller (1962) concludes that the weathering process is complicated by the climate of both the surface and subsurface strata. The weathering of the coarse grained mineral biotite is fairly rapid as compared to the stable mineral orthoclase and most stable minerals of muscovite and quartz (Graham, 1950). No information relating weathering of a particular rock type or mineral to changes in permeability was found in the literature. It seems reasonable to conclude, however, that as minerals weather to other products of decomposition, they change the soil's permeability.

The work of the scientists cited and others too numerous to mention exhibit the complex phenomena involved in soil permeability studies. The conclusion is drawn from the literature review that hydraulic conductivity is controlled by numerous factors. Schiff (1953) states that, "There appears to be no one known tangible characteristic that correlates directly with hydraulic conductivity". However, the review of the literature seems to indicate that the volume of large pores has a very dominant affect on hydraulic conductivity.

A Factor Selection Approach

Permeability has been related to numerous factors and has been found most often to be given as a function of a single important variable. Musgrave (1955) lists the major factors that affect permeability as: (1) surface conditions and the amount of protection against the impact of rain; (2) internal characteristics of the soil mass, including pore size, thickness of the permeable layer, swelling of clay, organic matter content, degree of aggregation; (3) soil moisture content; (4) duration of rainfall; (5) season of year and temperature of rainfall and soil. Each factor demonstrates the complex phenomena involved in hydraulic conductivity measurements.

The above factors are all influenced by many other parameters some having been studied in great detail and others only indirectly. The important point to consider here is the interrelationships which exist among the measured parameters of this study and whether the interrelationships would affect the selection of variables in a multiple variable equation.

Multivariate statistical analysis has been used successfully where there is a high degree of interdependency among variables. Multivariate analysis is that branch of statistical analysis which deals with the study of arrays of variables (Harmon, 1960; Kendall, 1961). A virtue of multivariate techniques is that they permit the simultaneous consideration of the source of variability from all the variables rather than minimizing the variations with respect to single dependent variables. For the simple mean and variance of a single variable, the concept of vector means and a matrix of covariance of several variables is substituted. This concept allows the association of error with more than one variable (Snyder, 1962).

Several hydrologic studies have applied (Anderson and West, 1965; Snyder, 1962; Wallis, 1965a, 1965b; Wallis and Anderson, 1965; and Wong, 1963) multivariate analysis techniques very successfully.

They used a principal components solution, a type of multivariate analysis, for purposes of (1) condensing a large number of variables by expressing them in terms of a small number of linearly independent factors, or (2) finding the underlying cause and effect factors that operate to produce the measurements of the variables, and (3) testing hypothesis concerning the underlying factors. Matalas and Reiher (1967) in commenting on current knowledge and usage of multivariate statistics which emphasize factor analysis and principal components analysis, contend that factor analysis is not a very useful tool because it is technically underdeveloped and the resulting factors are not observable nor expressible in terms of hydrologic parameters. Principal components solution is suggested as an alternative analysis when trying to find useful groups of factors. Principal components analysis with varimax rotation (Kaiser, 1958) appears to be a useful tool for determining if measured variables will serve as sensitive indicators of permeability. The varimax rotation developed by Kaiser (1958) simplifies the factors retained in order to give them a rational interpretation. The frame of the reference of the common factors (principal components) was rotated such that each factor ends up with high coefficients for just a few variables and low coefficients for the rest. This rotation then makes it possible to name each factor as expressing some particular characteristic of the data.

Permeability Measurements

Permeabilities are often determined by use of ring infiltrometers. However, some investigators claim ring infiltrometers may have some inherent limitations which may affect their usefulness. In the case of the double ring installation, the water for lateral flow is presumed to come from the outer ring and it is assumed that the outflow velocity from the inner ring represents the one dimensional infiltration velocity of the soil. Nelson and Muckenhirn (1941a, 1941b) reported velocities of the inner ring to be expressing one dimensional flow velocities. Lewis (1937) and more recently Bower *et al*. (1951) showed that the velocity in the inner ring compartment was less than that in the outer ring compartment. Schiff (1953) and Burgy and Luthin (1956) gave results that showed very little difference between single and double ring infiltrometer velocities. Swartzendruber and Olson (1961a, 1961b), have shown that ring size, texture of the soil system, and the depth of wetting front may cause the infiltration velocity to overestimate the infiltration rate. Whether single or double ring velocities were given as true velocities of infiltration seemed to be a function of whether the study was performed in the field or in the laboratory. Double ring infiltrometers were credited with giving true velocities under laboratory conditions because field experimental conditions were harder to control. Wilm (1941) concluded that the variation due to the soil and vegetative differences between any two adjacent infiltration study sites can be expected to far exceed any errors due to the measuring apparatus.

Permeability has also been studied with various other types of infiltrometers. Parr and Bertrand (1960) give a thorough review of the topic of infiltrometer measurements and types of infiltrometers that have been used. The numerous approaches for measuring infiltration points out the great diversity of methods and illustrates the fact that no one method yet developed meets all needs.

Infiltration equations yield maximum and minimum rates for each site. Horton (1936) found the minimum infiltration rate to be most closely associated with hydraulic conductivity and that surface runoff occurs when rainfall intensity exceeds the infiltration rate of the profile. The minimum rate is closely associated with hydraulic conductivity because it is responding to saturated conditions. The available information about the relations between field moisture content and water entry conditions prevailing during rainfall is rather inconclusive which is the reason infiltrometer studies have been undertaken.

Rubin and Steinhardt (1963) and Rubin et al. (1964), using a model which assumes Darcy's equation is applicable, developed a mathematical theory for predicting that ponding of water results only when rain intensity exceeds the hydraulic conductivity of saturated soil. The same idea may be applied to storms that produce surface runoff.

Laboratory measurement of hydraulic conductivity is done in a straight forward manner. The measurement consists of passing water through soil cores held in cylindrical containers. Disturbed or undisturbed cores can be used to determine permeability (U. S. Dept. of Agriculture, 1954). Marshall (1959) cites some of the difficulties involved with obtaining laboratory hydraulic measurements. The two most common problems encountered are water passing between the soil core and retaining ring and the dispersion or rearrangement of the soil particles by the moving water. Reeve (1957) presents details of methods for taking cores and using them for laboratory permeability measurements.

Computation of Darcy's Equation

Hydraulic conductivity values were most often calculated using the Darcy equation where:

$$K = \frac{Q\ L}{A\ H}$$

and

K = average hydraulic conductivity in inches per hour

Q = average volume of water passing through the sample expressed in cubic inches per hour

L = length of sample through which the water is passing and expressed in inches

A = cross sectional area of the sample and expressed in square inches

H = hydraulic head in inches

When there is a chance of nonproportionality Swartzendruber (1966) notes that Darcy's law should be used primarily as a working hypothesis type of first approximation. His comment implies that the possibility of nonproportionality be kept in mind as a possible explanation of discrepancies between Darcy based flow theory and actual experiments and that the validity of Darcy's law be checked independently for a given flow material.

Whipkey (1966) questions applicability of the Darcy equation for the calculation of hydraulic conductivity in forest soils. The reason for his rejecting the Darcy equation was because turbulent flow was thought to exist within the profile. Unfortunately no supporting data were presented to support his conclusions.

Meinzer and Fishel (1934) concluded from their tests of permeability with low hydraulic gradients that laminar flow occurs in porous media. The tests also show that no known lower limit exists for Darcy's equation. Wenzel (1942) concluded from reviewing early studies that: (1) the Darcy equation can be used only when the ground water flow is of the laminar type, and (2) there is extensive evidence that much of the observed ground water movement is of the laminar type and closely follows Darcy's law.

The problem with using the Darcy equation to calculate hydraulic conductivity is to verify whether laminar or turbulent flow conditions predominate. There is no well defined breaking point between the two types of flow (Todd, 1959). Todd states, "Darcy's law governs flows only when resistive forces predominate; therefore, when the inertial forces approach the same order of magnitude of the resistive forces, Darcy's law is inapplicable. This transition occurs before and separate from the incidence of turbulence". The transition occurs first in the larger pores and then, at higher flows, in the smaller pores as well.

Reynolds number criteria have been used by Wenzel (1942) to establish the limit where laminar flows no longer predominate. The Reynolds number is a dimensionless ratio which expresses the ratio of inertial to viscous forces in a fluid flow. Rose (1960) determined the upper limit of the Darcy equation by plotting the dimensionless Fanning friction factor used in hydraulics against the Reynolds number. Todd (1959) plotted the results of several studies using the technique. The upper limit of the Darcy equation was reached where the departures from a linear relationship began to appear. Departures from linearity begin to appear between Reynolds numbers of about 1 and 10. Scheideggar (1960) places little value on the several Reynolds number friction factor methods used to determine type of flow. His objection is that agreement among computed results is rare because of variations among the data.

The literature leaves no doubt that the Darcy equation is valid for only laminar flow. However, the criteria for deciding the flow measurement technique to use for a particular parent material type is not well established. Childs and Collis-George (1950) state, "There is considerable divergence of opinion as to the significance of such measurements. Some engineers report them without comment as a matter of fact routine whilst other observers have dilated the often uncontrollable variation of permeability measured in this way during the course of any single experiment and have provided fairly considerable literature in an attempt to account for these apparent variations and to indicate an interpretable technique".

DESCRIPTION OF THE STUDY AREA

The San Dimas Experimental Forest (Figure 1) lies on the south slopes of the San Gabriel Mountains. This research area has the desirable feature of being representative of much chaparral-covered mountain land in southern California. Results of the research program have specific application to the brush covered mountains of the region.

Soils

The soils of the study area are very immature (Storey, 1948) and are closely correlated with the parent materials, consisting of physically disintegrated parent rock. A brief description of soil within the study area was made by Crawford (1962). No attempt was made to correlate the survey results with the national soil classification system. The soils are excessively-drained, shallow, coarse-textured, and usually gravelly and stony throughout the profile. The sample locations, like most of the San Dimas Experimental Forest, have soils showing little or no profile development. The soils are classified as azonal and are lithosolic. The transition from the soil to the underlying decomposed parent material is very gradual. The soils have a weak, angular, blocky structure. Their consistency is loose when dry, and loose to friable when moist. Soil depths are generally less than 24 inches, measured vertically.

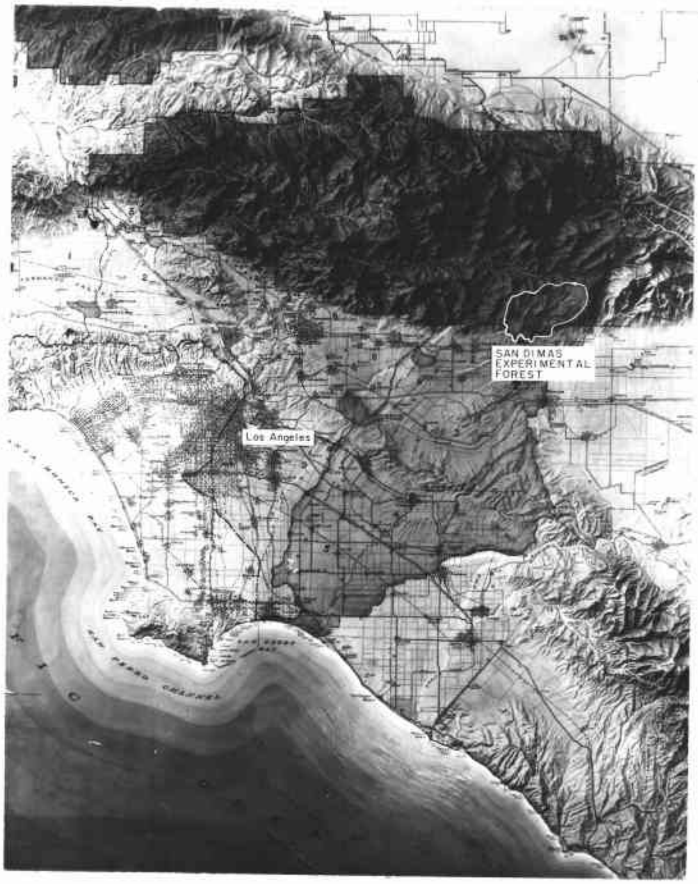


Figure 1. Location of the San Dimas Experimental Forest.

Soil moisture is at or below the wilting point at the beginning of the rainy season and the capacity to store water is at a maximum (Rowe and Colman, 1951). Since the soils are shallow, surface runoff would occur if the soil mantle were the only place to store water from intense storms. Drainage into the underlying parent material is presumed to begin as soon as the soil reaches field capacity (Storey, 1948).

Bentley's (1961) summary of soil depths shows that 74 percent of the San Dimas Experimental Forest has soils less than 2-feet deep. Extrapolating these data to include the San Gabriel Mountains would show at least the same percentage of land area having a shallow soil mantle.

Geology

The formation important to this study is the igneous formation which consists largely of granitic types, varying from true granites, granodiorites, granite diorites to diorites (Bean, 1945). These rocks also underlie the major portion of the San Gabriel Mountains.

Several periods of uplift and submergence have occurred in geologic time which have subjected the parent material to all recognizable types of alteration including folding and faulting, extensive weathering and erosion. The great amount of jointing and fracturing has allowed ready access of weathering agents. Weathering is deep and results in considerable variation of the water-carrying capacity of this formation (Bean, 1945).

Vegetation

The major plant formation of the area is chaparral. Important chaparral cover types found on the study sites are chamise (*Adenostoma fasciculatum*), hoaryleaf ceanothus (*Ceanothus crassifolius*), black sage (*Salvia mellifera*), California buckwheat (*Erigonum fasciculatum*), and California scrub oak (*Quercus dumosa*).

All the species comprising the chaparral formation are able to withstand long, dry summers. Brush becomes very flammable during the rainless periods. During the last 65 years most of the chaparral cover has been burned-over at least once, according to Ferrell's (1959) summary of fire records. Chaparral vegetation has the ability to perpetuate itself in spite of burning. However, increased surface runoff and erosion occur for many years while the brush is recovering (Rowe, Countryman, and Storey, 1954).

Climate

The area has a Mediterranean climate which is characterized by long, warm and dry summers and wet winters. The average annual precipitation for the study area is 25.63 inches, based on the period of record 1933 to 1966. An official U. S. Weather Bureau climatic station is located within one-half mile of each of the individual sample locations. Analysis of precipitation records shows that 96 percent of all precipitation occurs from October to and including April. The four wettest months, December, January, February, and

March have 73 percent of the total annual rainfall (Hill, 1963). A storm class distribution shows 27 percent of the total precipitation fell in 4 percent of the storms and 53 percent of the storms produced only 8 percent of the rainfall (Hill, 1963).

Torrential winter storms and resultant high stream discharges are typical of the mountain areas. Damaging floods occur about once in every 5 to 6 years.

FIELD MEASUREMENTS AND SAMPLING PROCEDURES

Infiltration Measurements

Infiltration measurements were made with a double-ring infiltrometer in the bottom of contour trenches in the Tanbark Flat area of the San Dimas Experimental Forest. Figure 2 shows a completed contour trench and storage basin. The trenches were constructed in randomly selected watersheds 3 to 8 acres in size as part of a post-fire study (Rice et al., 1965). Each watershed contains 3 or 4 trenches. Trench depths range for 2 to 6 feet below the original soil surface, thus exposing the parent material. Locations of sample sites within the study area appear in Figure 3. Reference to the Rowe-Colman plots are noted because soil moisture data from these plots are used in later calculations. Twenty-seven locations were selected within a square-mile area for sampling hydraulic conductivity. A description of the infiltrometer instrumentation at each location is shown in Figure 4.

The infiltrometer sites were systematically located within the study watersheds. All of the watersheds were in steep terrain which put an economic limit on the number of samples which could be taken. The systematic selection of the sites consisted of locating a sample point in each trench. The first 2 or 3 sample sites (depending on number of trenches within a watershed) from the top of the watershed were located in the third basin in the trench looking

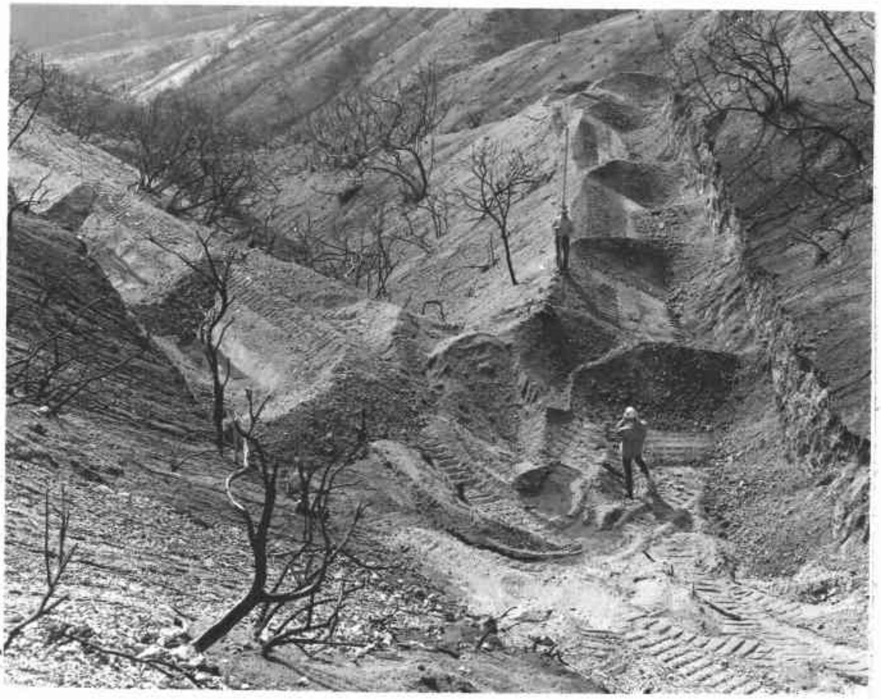


Figure 2. Completed contour trench showing storage basins and location of a possible sampling site.

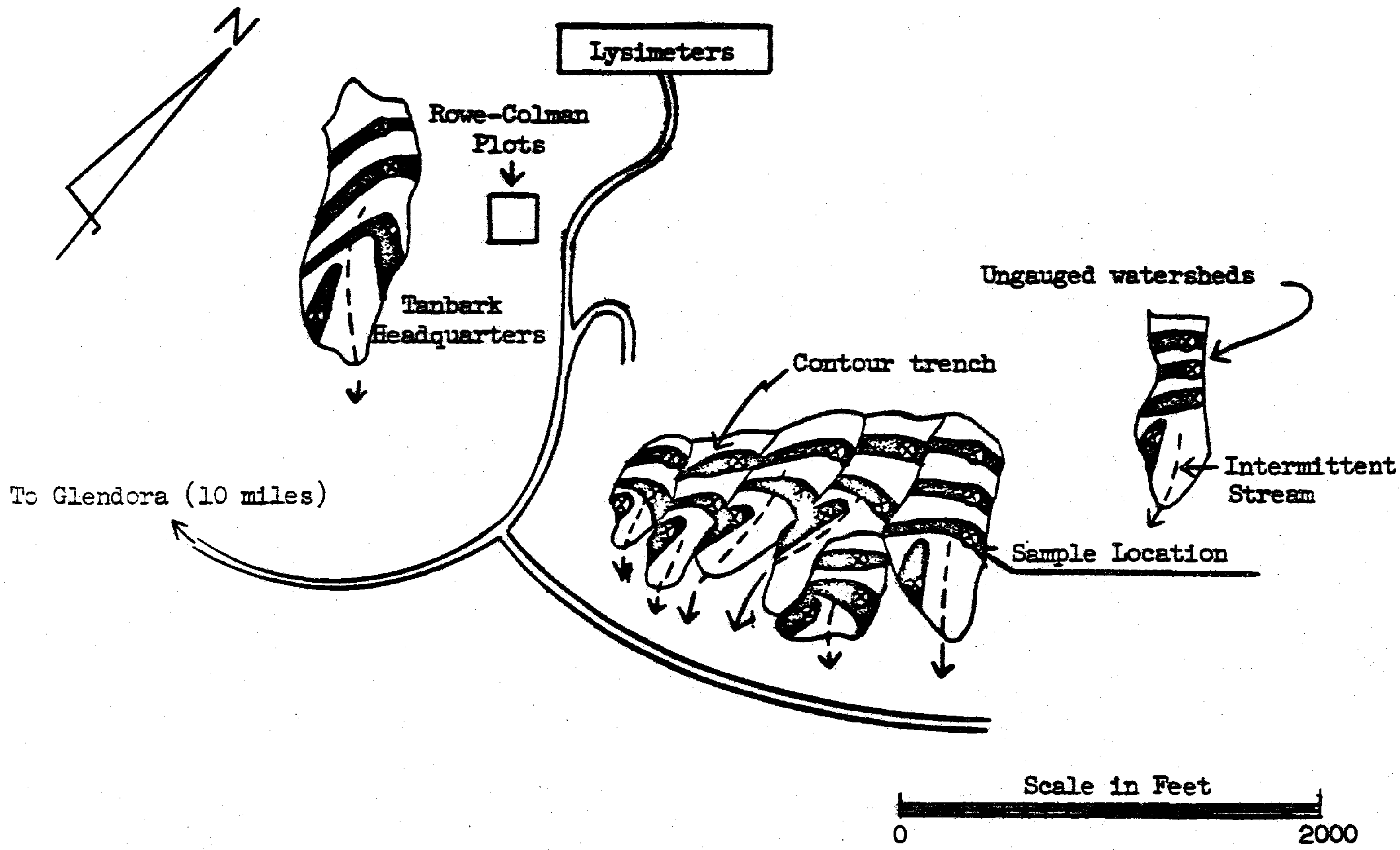
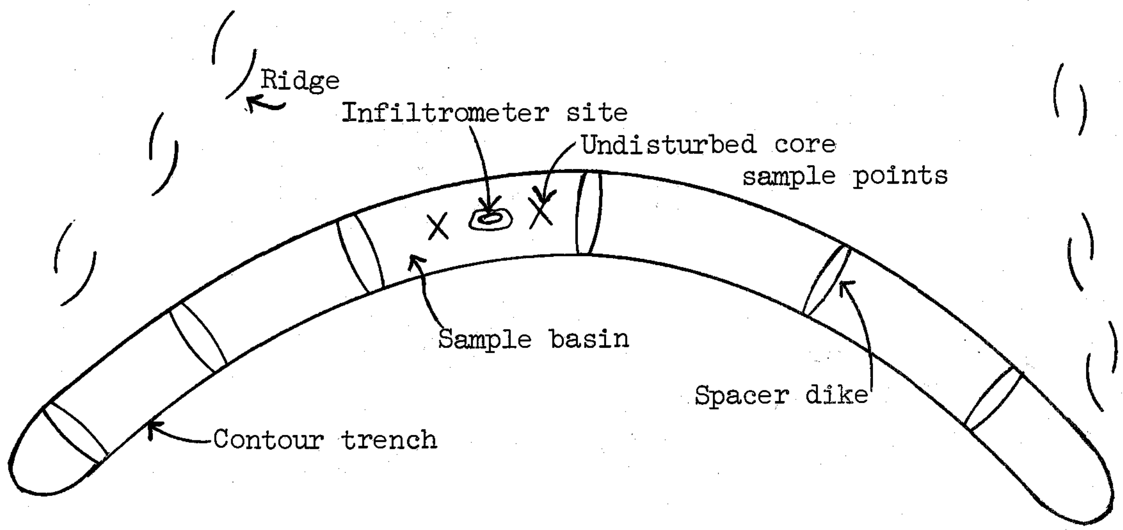


Figure 3. Schematic drawing of the double-ring infiltrometer and undisturbed-core sample sites.



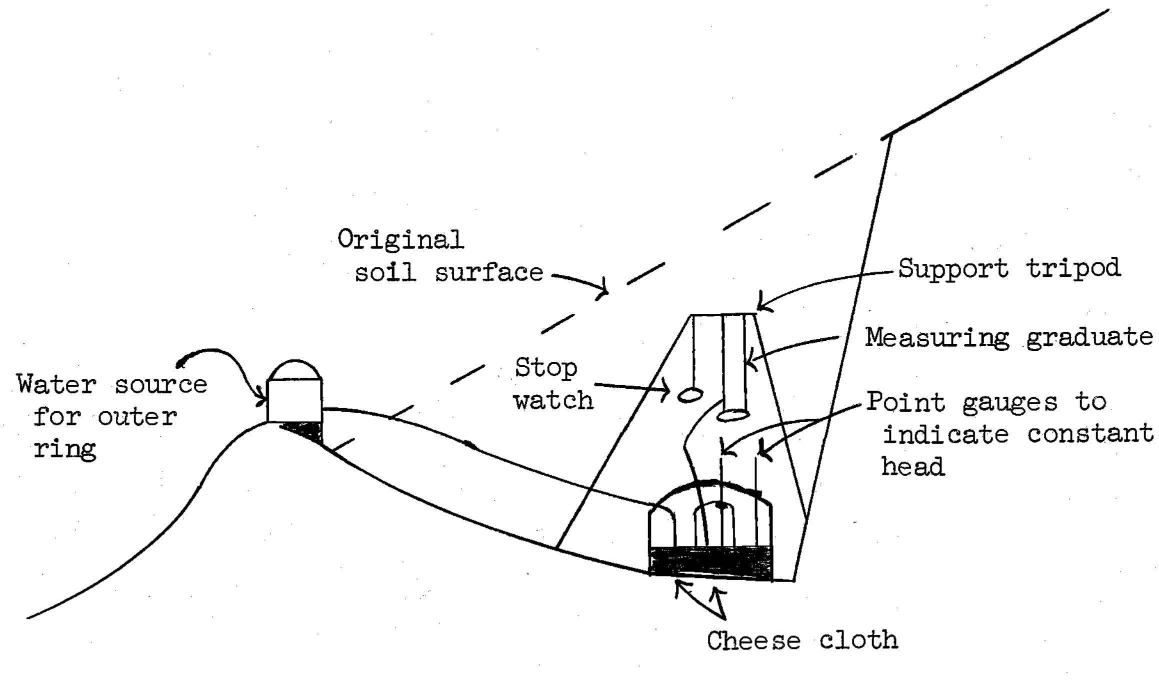


Figure 4. Schematic drawing of a top and cross-sectional view of a double ring infiltrometer sample location.

toward the west (Figure 3). A sample site nearest the mouth of the watershed was located in the third basin looking to the east. The lowest trenches are shorter and originate on the west slopes. All 27 sampling points were in remote locations which required the water to be carried to the sample locations.

The inner ring diameter was 6.25 inches and the outer ring diameter was 12.5 inches. Ring material was 0.25 inch steel pipe which was beveled on one end to allow the ring to be driven into the parent material with greater ease. The rings were 12 inches long and were easily driven in place with a small sledge. Cheese cloth was placed in the bottom of the rings to prevent disturbance of any particles while a head of water was being introduced. A 7 inch constant head was maintained in both inner and outer rings by a controlled flow from the water sources. A point gauge was clamped to the rings to indicate the head height.

Infiltration data were recorded for only the inner ring. This was done by timing the outflow from the measuring graduate which was used to maintain a constant head of water (Figure 4). The 27 infiltration runs lasted for a period of about one hour and were not repeated. Field sampling was done during September and October of 1964 before winter rains occurred and field moisture contents were at the wilting point.

Conversion of Infiltration to Hydraulic Conductivity

An objective of the study was to compare hydraulic conductivity measurements of the ring infiltrometer with those calculated from laboratory techniques. In order to compare the methods, ring infiltrometer data were corrected for temperature and converted to comparable hydraulic conductivity values. The Darcy equation described earlier was used to calculate hydraulic conductivity values.

The parent material beneath the inner ring was assumed to function in an identical manner to that of samples used for laboratory hydraulic conductivity measurements. Inflow rates were used as the (Q) values in the Darcy equation.

Water temperatures were measured in the inner ring during field sampling. Differences between the field water temperatures and a standard temperature were adjusted by using the ratio;

$$\frac{\text{absolute viscosity of water at field temperature (poise)}}{\text{absolute viscosity of water at a standard temperature (poise)}}$$

which adjusts for fluid viscosity. The corrections were applied to the field hydraulic conductivity values to adjust the flow rates to temperatures expected during storms.

Undisturbed Core Samples

Undisturbed core samples were taken with the San Dimas sampler (Andrews and Broadfoot, 1958) for use in subsequent laboratory analysis. This sampler was specifically designed for extracting undisturbed samples in granitic parent material. The hand operated sampler utilizes an auger-type cutter rotating around a stationary inner collector ring. The collector rings are 3.0 inches in diameter by 2.0 inches long, producing a core 2.87 inches in diameter by 2.0 inches long.

Four samples were extracted at each location at a distance of 6 inches away from the edge of the outer infiltrometer ring. They consist of two sets of duplicate samples on each side of every infiltrometer location, totaling 108 core samples. The two sets consisted of samples taken to 2 inch and 6 inch depths at the bottom of the trenches in the parent material.

The core samples were extracted just prior to the beginning of the infiltration runs. The samples were stored in soil moisture cans for later determination of field moisture values.

LABORATORY MEASUREMENTS AND DATA COMPUTATIONS

There is a need for estimation of hydraulic conductivity values without laborious and time consuming measurements as carried out in the field. Therefore, laboratory measurements of porosity, bulk density, particle density, moisture detention and retention, mineral content, particle size distribution, and hydraulic conductivities were made from the undisturbed parent material cores. These measurements were made to determine if more quantitative information on hydraulic conductivity could be gained through laboratory analysis rather than through limited field measurements.

All undisturbed core samples were analyzed in a constant temperature room (22°C) at the Tanbark field laboratory.

Hydraulic Conductivity

Laboratory hydraulic conductivity measurements are generally made at much higher temperatures than actually exist during storm periods. A variation in viscosity of water can be produced by changes in temperature. The storm air temperatures within the study area average about 6°C. It is assumed that the temperature of the percolating water during these frontal storms will be about the same as the air temperature (Byers, 1949; Erie, 1962). Soil temperatures at the 6 inch depth average 6°C during the rainy season (Qashu and Zinke, 1964). For this reason, a low temperature water bath was used to circulate cooled water around and through the cores to maintain a constant $6^{o}C$ temperature. The water jacket and permeameter system are shown in Figure 5.

In operation (Figure 6), the cooled water enters the water jacket system at (1) and moves into the permeameter through a brass tube (2) and flexible plastic tube connection (3). The brass tube has the added advantage that if entrapped air is in the system a bubble will form on top of the tube. The air is removed by inserting a brass rod into the tube (2) allowing the bubbles to rise. Water flowing through the rock core (4) passes through the outlet (5) to the measuring graduate. A 7 inch head was maintained in the permeameter system by locating the outlets to the water bath (6) and measuring graduate (5) the desired distance apart. Inlets to the water jacket (7) allowed cooled water to circulate around the core sample and aid in maintaining a constant temperature of the water moving through the core. No water entered the permeameter from the cooling jacket. Thermometers served to check the temperature of the circulating water.

Each core was thoroughly saturated from the bottom to remove any entrapped air present in the system before data runs began. Measurement of inflow into the graduate was not started until the cores had reached a constant rate of flow which was assumed to be the point when the cores were thoroughly saturated.

Laboratory hydraulic conductivity values were calculated using the Darcy equation as defined previously.

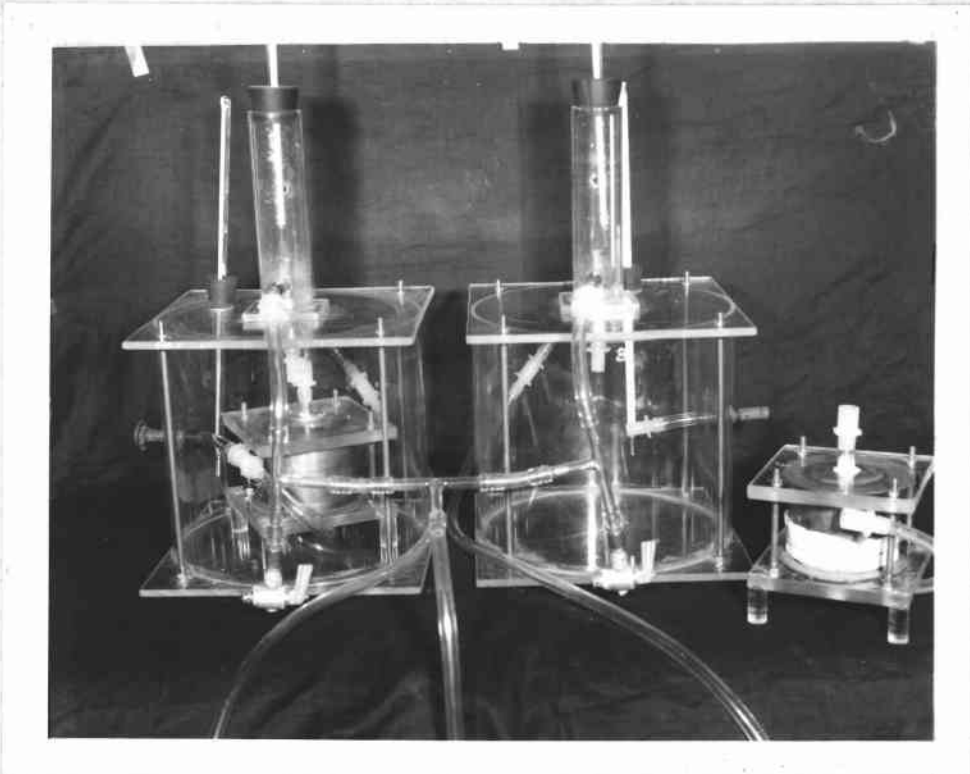


Figure 5. Low temperature water bath jacket and permeameter used for hydraulic conductivity measurements.

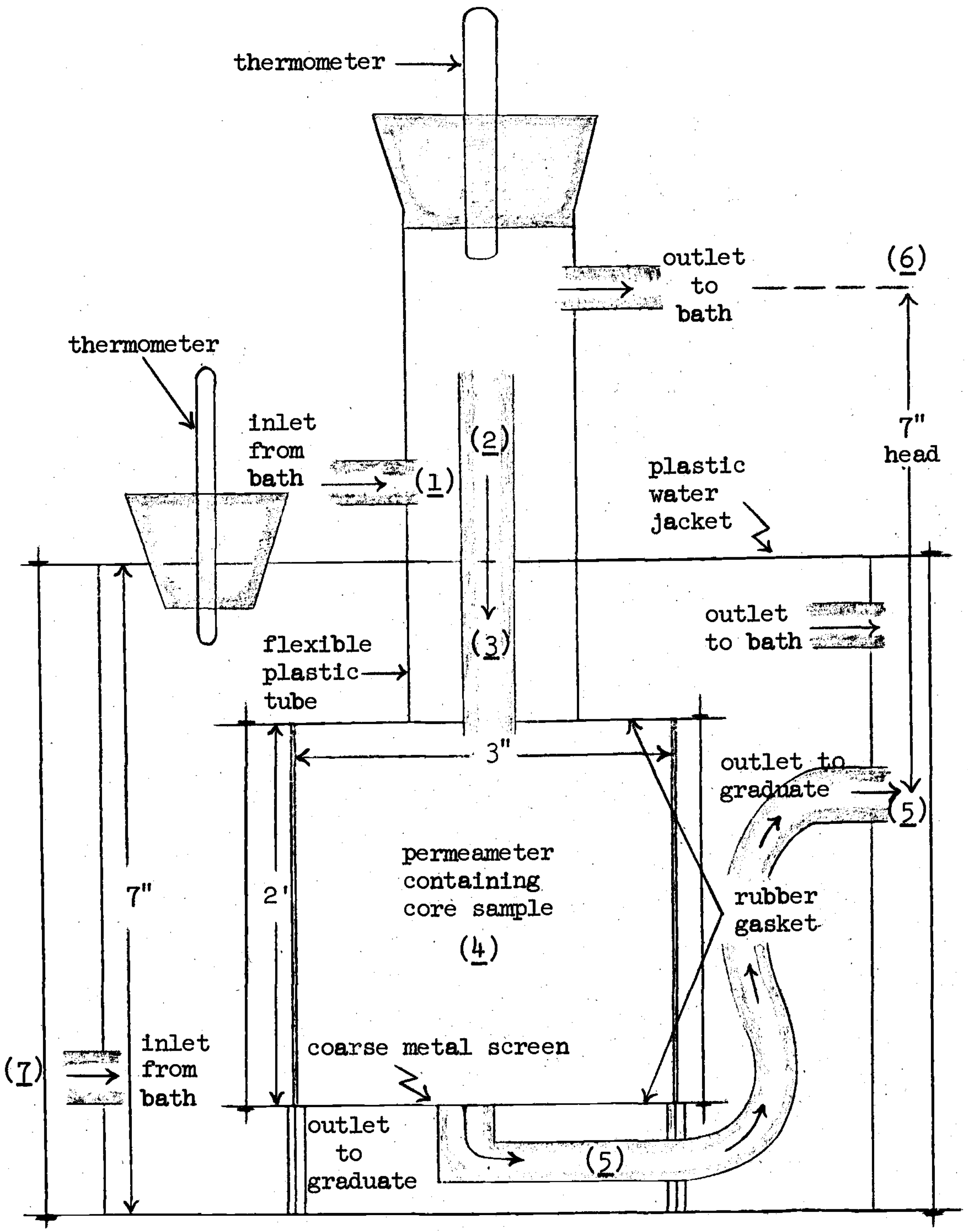


Figure 6. Diagram of permeameter and cooling jacket.

No temperature corrections were necessary for the laboratory samples because the low temperature water bath maintained a constant 6°C.

Reynolds Numbers

A basic assumption to this problem was that the Darcy equation was a valid equation to compute hydraulic conductivity of the parent material. The outflow velocities were used in the calculation of Reynolds numbers to see if laminar flow did, in fact, exist. The Reynolds numbers were calculated in the following manner:

$$N_r = \frac{\rho v d}{\mu}$$

where:

ρ = the density of water in grams per cubic centimeter

v = apparent velocity in centimeters per second

d = average grain diameter of the sample in centimeters

μ = absolute viscosity of the fluid in grams per centimeter per second

Total Porosity

Porosity is cited as being a significant variable affecting permeability. Instruments for determining field porosity quickly and easily have been developed and field tested. Several investigators (Jamison, 1953; Kummer and Cooper, 1945; Page, 1948; Russel, 1950; Steinbrenner, 1959) have designed and used various types of air pycnometers for investigating certain soil physical properties. They reported that total soil porosity, macro-microsoil pore space distribution, and soil bulk density could be determined rapidly and accurately with the use of air pycnometers.

An air pycnometer has been designed, tested and was used for measuring total porosity of the undisturbed core samples. In operation, the air pycnometer utilizes a very sensitive air pressure test gauge to read the change in air pressure which indicates the differences in volume of solid materials (Figure 7). This pycnometer utilizes three air systems: (1) fine adjustment system, (2) constant volume system, and (3) a soil chamber system. A soil core is placed in the air tight soil chamber (on the right in Figure 7). Air pressure in the fine adjustment system and constant volume system (left-side chamber) is brought to about 14 psi. The valve on the left is closed and the two systems are adjusted to exactly 14 psi, using the fine adjustment needle valve on the sealed lid of the constant volume chamber. The right valve is then opened, allowing the air pressure in both chambers to equalize. Air pressure changes in the two systems are directly related to changes in volume of the soil solid in the soil chamber.

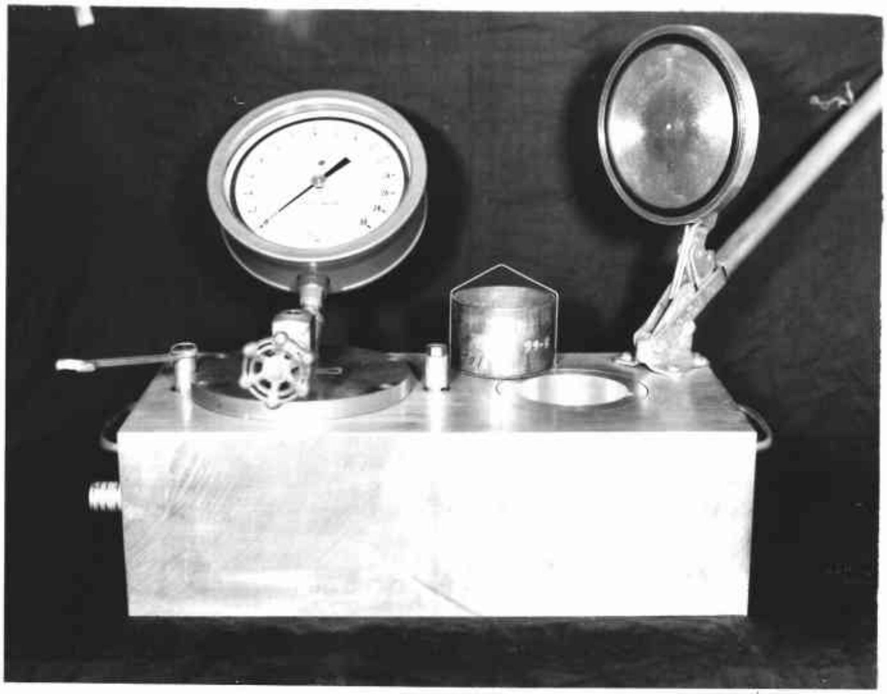


Figure 7. Aluminum block air pycnometer. (Note: Cresent wrench resting on left valve - needle valve and test gauge are positioned on the cover lid of the constant volume chamber.)

Particle Density and Bulk Density Determination

Particle density and bulk density measurements were made for each of the laboratory core samples to be used as a quantitative parameter of hydraulic conductivity and as a parameter in the calculation of total porosity. For measuring particle density, specific gravity bottles were weighed when containing only air (W_a), when filled with water (W_w), and when filled with oven dried parent material samples (W_p), and when completely filled with parent material and water (W_{pw}). The specific gravity bottles containing samples completely filled with parent material and water were allowed to stand for 5 days to allow for complete filling of all the pores and eliminate entrapped air. The bottles were refilled when necessary and the weight (W_{pw}) checked (U. S. Dept. of Agriculture, 1954). The particle density (P_d) of the material in grams per cubic centimeters was then determined by:

$$P_d = dw\ (W_p - W_a)\ /\ (W_w + W_p - W_a - W_{pw})$$

where (dw) was the density of water (22°C) in grams per cubic centimeter.

Bulk density measurements were made using the oven-dry weight of the sample and the calculated volume of the core samples were:

$$\text{Bulk density} = \frac{\text{weight of oven-dry soil core}}{\text{field volume of the sample}}$$

Results were expressed as grams per cubic centimeter (U. S. Dept. of Agriculture, 1954).

The particle density and bulk density values were also used to calculate the total porosity of each sample. The calculated porosity values were used as a comparison for the air pycnometer porosity method. A Student's "t" test for unpaired comparisons was used to evaluate the air pycnometer method. There was no significant difference between the sample means at the 95 percent level of significance (see Appendix 3, Table C). The air pycnometer porosity values were used for all further calculations involving porosity.

Particle Size Distribution

A particle size distribution analysis was made following a dry sieve analysis (U. S. Dept. of Agriculture, 1954) on each of the 52 samples used in the parameter evaluation of hydraulic conductivity. Size classes were set at greater than 2 millimeters, 1-2 millimeters, .5-1 millimeters, .25-.5 millimeters, and less than .25 millimeters. Samples were oven dried at 105°C and subjected to a 5 minute agitation in a sieve shaker to separate the particles. The distribution consists of the ratio of oven-dry weight of material remaining on each sieve to the total weight of the sample. A median particle size was determined by plotting the cumulative relative frequency of particle sizes and obtaining from the curve that size which composed 50 percent of the sample. The average particle size was assumed to be equal to the median point.

Moisture-Suction Curve

The purpose of the moisture-suction curve was to derive storage characteristics for the parent material. Moisture storage values were used to determine the pore size distribution for the parent material. A moisture-suction curve was constructed by making a plot of the percent moisture retained at pressures of 60 centimeters (water), 1/3 atmosphere and 15 atmosphere.

The 60 centimeter moisture values for the 52 samples were determined from a moisture-suction table (Broadfoot and Burke, 1958). The 60 centimeter values were also used in the statistical analysis as an expression of non-capillary porosity.

One-third atmosphere moisture values were determined for the same samples by use of a pressure plate apparatus (Richards, 1948). The 15 atmosphere or wilting point storage values used were the moisture contents at time of field sampling (Rowe and Colman, 1951). The 52 samples which were used for laboratory determinations were stored in soil moisture cans in order to determine the field moisture content. Weights for field moisture were taken before other analyses were undertaken.

A similar moisture-suction curve was prepared from the surface soil of the study area using data obtained by Rowe and Colman (1951). Surface soil storage characteristics were used to evaluate the occurrence of saturated moisture movement. These data were reported as the average values obtained from 110 soil survey pits and the two year average of 14 moisture sampling plots.[1]

Pore Size Distribution

Pore radii and pore size distributions were calculated from the moisture-suction data. The pore size distributions were used to: (1) determine the volume of water necessary to saturate the surface soil and parent material, and (2) determine if the pore distribution influences surface runoff (Childs and Collis-George, 1950; Marshall, 1958).

The moisture content value is related to the withdrawal of moisture from pores against the surface suction forces. Therefore, the moisture-suction curve is an indication of the pore size distribution of the soil and parent material (Remson and Randolph, 1962).

The pore radii were obtained by solving the capillary rise equation for given suction values. Pore sizes were computed for both surface soil and parent material. The classic capillary rise equation (Baver, 1956) was used:

$$h_c = \frac{2\gamma}{\rho\, g\, r} \cos\,\theta$$

[1]Particle density, 60 centimeter moisture tension values and hydraulic conductivity values for the surface soil and 1/3 atmosphere parent material core data were supplied in a personal communication from Dr. Leonard F. DeBano, Soil Scientist, of the Experiment Station staff.

where:

h_c = height of capillary rise or in this case the moisture-suction values in centimeters

γ = surface tension of the fluid in dynes per cubic centimeter

ρ = density of water in grams per cubic centimeter

g = gravitational acceleration in centimeters per second squared

r = radius of the pore in centimeters

$\cos\,\theta$ = angle of contact between the liquid and the solid (assumed to be zero contact angle)

Pore sizes were calculated for pores which would support a column of water against a suction pressure of 60 centimeters, 1/10 atmosphere, 1/3 atmosphere, 1, 2, 5, 10, and 15 atmospheres.

The pore size distributions were obtained from the moisture-suction curve. The moisture-suction curve gives the volume of moisture which is retained in the voids at a given suction. The pore size distributions were obtained by calculating the volume of voids that were drained at suctions of 60 centimeters, 1/10 atmosphere, 1/3 atmosphere, 1, 2, 5, 10, and 15 atmospheres.

Mineralogical Determination

A mineralogical determination was made to; (1) identify the parent material type, (2) determine if the minerals making up the rock matrix may be significantly correlated with saturated hydraulic conductivity, and (3) establish if a particular parent material type had any relationship to hydraulic conductivity. One set of the duplicate core samples was used for the petrographic determinations. No other laboratory measurements were made on these cores. Identification of the parent material and mineral composition was contracted.[2] The investigation involved a modal analysis of thin-sections; consisting of a systematic grain count to identify the minerals present in each sample. The relative abundance of the minerals is expressed as a percent of the total sample which is the value used in the statistical analysis.

The major mineral content of the granitic parent material is quartz, potash feldspar, plagioclase feldspar, biotite, and muscovite. Minerals appearing in trace amounts were not used in the statistical analyses. No attempt was made to determine the type of clay present in the core samples.

[2]The mineralogical determination was performed by Mr. Donald O. Doehring, a graduate student in geology at Claremont Mens College, Claremont, California.

Rainfall Intensity Distribution

Rainfall intensity duration curves for point rainfall were developed based on 31 years of record. These curves are plotted in order to: (1) find the percent of storm precipitation falling at rates in excess of the storage requirements of the surface soil and parent material; (2) determine the percent of time a storm might exceed the hydraulic conductivity rate of the saturated soil; and (3) evaluate the several intensity periods for future use for predicting surface runoff. The annual series analyses were calculated for rainfall intensities over period of 15 minutes, 20 minutes, 30 minutes, 60 minutes, 24 hours, and the entire storm. Twenty-five years of rainfall data (1933 to 1958) were available from Reimann and Hamilton (1959) in addition to 6 years of unpublished data from the San Dimas Experiment Forest through hydrologic year 1965 (Appendix A).

Factor Selection

A factor selection was undertaken to determine the physical properties which would most effectively describe saturated hydraulic conductivity in the parent material. The factor selection technique consisted of simple correlation analysis and principal components analysis with varimax factor rotation.

Relationship Among Variables

The relationship among variables was determined by computing simple correlation coefficients for 21 measured variables of the granitic parent material. Table 1 shows the list of all the variables used for the factor selection analysis. The simple correlation coefficient is a measure of the degree of linear association between two variables and is free of the effects of scales of measurement. The objective of the correlation coefficient computation was to determine if relationships exist among the variables. Some variables, even though they were highly correlated with other variables, were rejected because they were joint variables, as in the case of the high interrelationship between bulk density, particle density, and median particle size. Other variables such as clay content and moisture content at time of sampling were dropped from further consideration because they contributed little to the analysis. A second matrix was computed for correlation coefficients of the remaining variables (Table 1).

Selection of Variables Describing Hydraulic Conductivity

Principal components analysis with varimax factor rotation was used as a tool to condense the remaining variables by expressing them in terms of a smaller number of linearly independent common factors (common factors are defined as groups of interrelated variables), and to determine which of the remaining physical

Table 1. Variables used for factor selection analysis.

Porosity*
Bulk density
Particle density
Non-capillary porosity*
Depth from soil surface*
Parent material type
Quartz content*
Orthoclase content
Plagioclase content
Biotite content*
Muscovite content
Clay content
Field moisture content
Greater than 2 mm particle size
1 - 2 mm particle size*
.5 - 1 mm particle size*
.25 - .5 mm particle size*
less than .25 mm particle size*
median particle size

Field hydraulic conductivity
Laboratory hydraulic conductivity*

*Indicates variables retained in second correlation matrix for use in the principal components analysis.

properties would most effectively describe saturated flow in the granitic parent material and serve as a sensitive indicator for permeability studies.

A principal components analysis rotates the reference axes of the variables to create new dimensions. The axis of the first principal component will be so oriented as to provide the maximum separation among the observations making up the multi-dimensional sample. This means that the first principal component will be a linear function of the original variates having the maximum variance. The second principal component will have its axis oriented orthogonally to the first principal component and with that restriction will explain the maximum amount of the variance of the sample, and so on. Each successive principal component is independent of its predecessors and explains less of the variance of any of its predecessors. If the variances of some of these later principal components are very small, the dimensionality of the multivariate sample is less than the number of variates currently being measured. A principal components analysis is the methodology most often used for striking a balance between the minimum number of common factors and explaining the maximum variation among the original variables.

The varimax factor rotation deals with making the common factors more interpretable. The purpose is to make the factors intelligible. If each common factor contains a few variables with high coefficients it is likely that the property of the data which this property is measuring can be named. By minimizing the number of factors to which a variable is highly correlated the chances are further improved that each common factor can be identified unambiguously. The varimax factor rotation (Kaiser, 1958) was employed in order to lead to the redefinition of measurable variables and lead to the uni-factor model describing the hydraulic conductivity of the granitic parent material.

A brief description of the computer programs utilized appears in Appendix B.

RESULTS AND DISCUSSION

The objective of this study was to find more quantitative information about the hydrologic properties of the granitic parent material. The results and discussion are presented under five topics: (1) the selection of the physical factors which best describe saturated movement of soil moisture, (2) whether there is a relationship between field and laboratory hydraulic conductivity techniques, (3) whether laminar or turbulent flow exists during saturated moisture movement through the parent material, (4) moisture-suction characteristics, and (5) pore size distribution of the surface soil and parent material. The latter two topics include discussion of the hydrologic application of these results to determine if saturated flow occurs during major flood runoff periods. The results of the parameters used to evaluate hydraulic conductivity are listed in Table 2.

Factor Selection

Relationship Among Selected Variables

The results of the simple correlation analysis are shown in Table 3. The variables bulk density, particle density, orthoclase, plagioclase, clay content, field moisture content, greater than 2 millimeter particle size, and median particle size were dropped from the analysis either because they were intercorrelated with other

Table 2. Range and average values of properties of the undisturbed core samples.

Variable Name	Range	Average
Porosity	22.5 - 49.6	37.0 percent
Bulk density	1.34 - 2.05	1.68 gm/cc
Particle density	2.27 - 3.08	2.68 gm/cc
Depth	2.5 - 5.5	4.0 feet
Quartz content	0 - 55	20.6 percent
Biotite content	0 - 24	12.0 percent
Muscovite content	0 - 2	0.2 percent
Plagioclase content	0 - 80	30.1 percent
Moisture content at:		
60 centimeters	20.1 - 32.5	22.1 moisture content percent by volume
1/3 atmosphere	8.2 - 20.4	13.1 moisture content percent by volume
15 atmosphere	0.4 - 6.3	3.6 moisture content percent by volume
Particle sizes:		
> 2 mm	7.1 - 64.1	12.6 percent
1 - 2 mm	7.3 - 33.7	18.3 percent
.5 - 1 mm	9.0 - 28.5	17.5 percent
.25 - .5 mm	5.2 - 21.4	13.0 percent
< .25 mm	5.1 - 41.2	19.4 percent
Median particle size	0.38 - 2.75	1.31 mm
Hydraulic conductivity:		
Field samples	0.087 - 3.283	1.11 inches/hour
Laboratory samples	0.035 - 4.961	0.99 inches/hour

Table 3. Simple correlation matrix from the parent material samples.

Column	tp	N-C	d	Q	B	1-2	.5-1	.25-.5	< .25	K(Lab)	K(Field)
Total porosity (tp)	1.00	.67*	.08	-.19	.37*	-.26	.23	.51*	.66*	.12	.07
Non-capillary porosity (N-C)		1.00	.22	.10	.21	-.01	.04	.16	.16	.44*	.09
Depth (d)			1.00	-.23	.31	-.24	-.26	-.16	.09	.21	-.05
Quartz (Q)				1.00	-.42*	.34*	.07	.01	.23	.14	.37
Biotite (B)					1.00	-.12	.18	.28	.29*	.08	.12
1 - 2 mm (1-2)						1.00	.50*	.08	-.44*	.20	.12
.5 - 1 mm (.5-1)							1.00	.80*	.27	.09	.21
.25 - .5 mm (.25-.5)								1.00	.70*	.18	-.26
< .25 mm (<.25)									1.00	-.28	-.23
Laboratory hydraulic conductivity (K Lab)										1.00	-.06
Field hydraulic conductivity (K Field)											1.00

* Significant at the 90 percent level.

variables or they did not contribute significantly to the analysis. However, the results for the moisture content, and median particle size variables were used in the interpretation of pore size distribution and Reynolds numbers.

Examination of simple correlation matrix shown in Table 3 indicates that only one variable, non-capillary porosity, had a significant relationship with laboratory hydraulic conductivity. None of the listed variables were significantly correlated with field hydraulic conductivity. These results indicate that it would be possible to predict hydraulic conductivity from knowledge of non-capillary pore space. Figure 8 shows the relationship between laboratory hydraulic conductivity and non-capillary porosity of the samples. The scattered data points indicate the variability which exists within the parent material.

Relationships of depth of sampling (from the original soil surface) to variables other than mineral content show no significant correlation. Physical parameters within the granitic parent material profile are quite complex and interrelated and show that a profile is far from being homogeneous in all respects.

The correlation analysis served only to identify the obvious relationships between individual variables and showed that significant relationships are not necessarily causally related, since both variables may be influenced by a third variable. Even when there is a causal relationship involved, the correlation coefficient does not in itself indicate which is cause and which is effect. It was

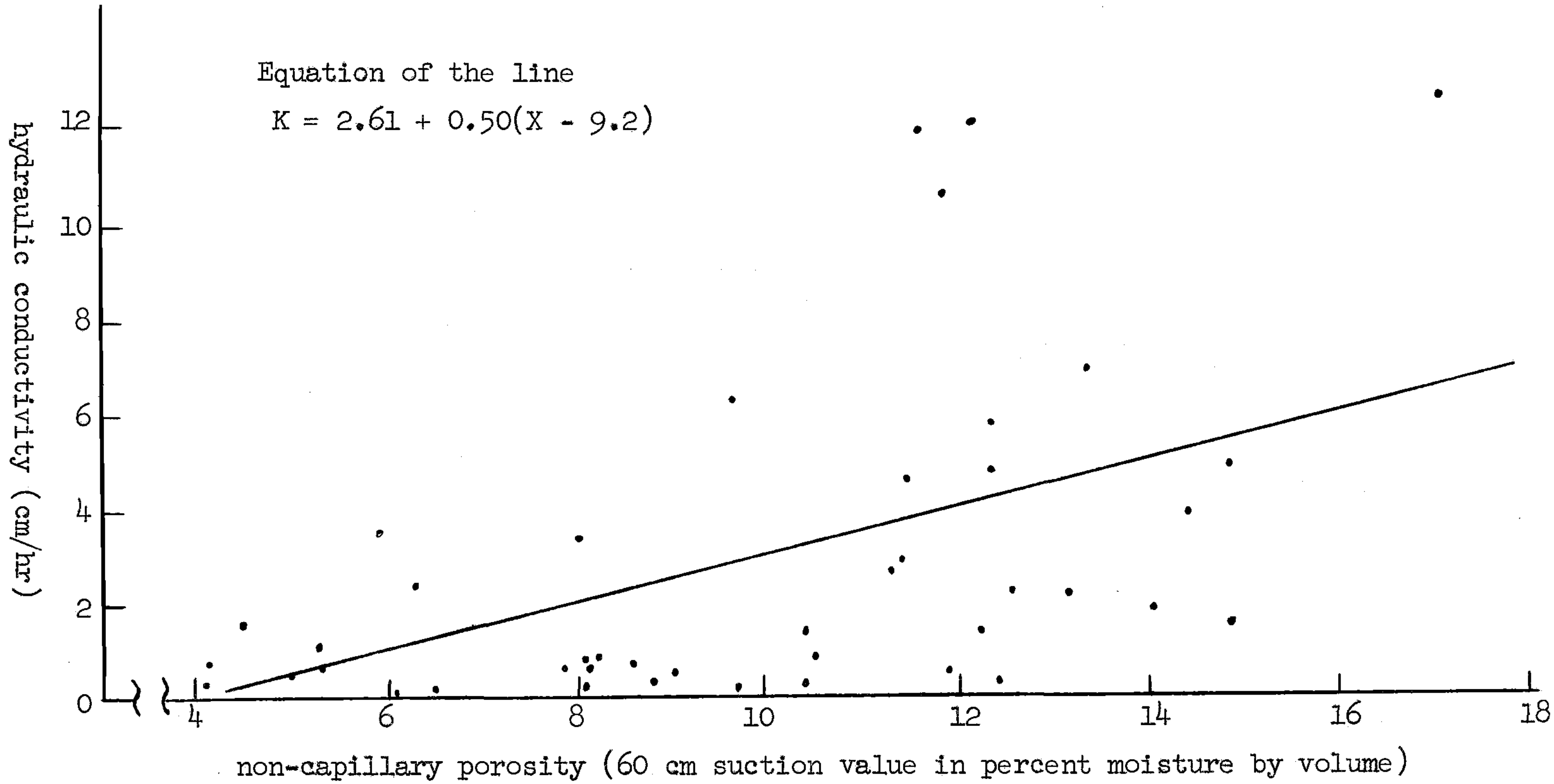


Figure 8. Relationship of non-capillary porosity to hydraulic conductivity.

necessary to use principal components analysis to facilitate the selection of a set of parameters for the evaluation of hydraulic conductivity.

Selection of Variables Describing Hydraulic Conductivity

The purpose of the principal components analysis with varimax factor rotation was to reduce the number of correlated variables to a smaller number of independent common factors which serve as a sensitive indicator for variables to measure in future permeability studies. Principal components analysis begins with the correlation matrix and reduces the observations to common factors. Five common factors explaining about 88 percent of the variation among the common factors were considered in this study (Appendix C, Table A and B).

The varimax factor rotation leads to a more easily interpretable solution in which each factor is conceived of as expressing some physical parameter relating to the granitic parent material (Table 4). Factor weights associated with each variable which had values less than 0.65 were not considered as defining the factor.

The rotated factor matrix values shown in Table 4 are the correlation of each variable with the common factors. The questions to ask of the factor weight matrix values: (1) Is each common factor representative of variables describing a single physical parameter? (2) Are there particular variables with a high factor weight associated with a single common factor, hence represent a single physical

Table 4. Varimax factor rotated matrix of the nine hydraulic conductivity variables.

Variables	Common Factors				
	1	2	3	4	5
Total porosity	.36	-.82	.17	.16	-.22
Non-capillary porosity	-.04	-.93	-.04	-.23	-.01
Depth	.11	-.12	.13	-.86	-.22
Quartz	-.12	-.02	.39	-.07	-.78
Biotite	.24	-.17	-.15	-.19	.82
1 - 2 mm	.18	-.03	.94	-.12	-.10
.5 - 1 mm	.82	.07	.31	-.34	.06
.25 - .5 mm	.98	-.19	-.06	.00	-.10
< .25 mm	.60	-.35	.35	.34	-.32

difference between parent material samples.

The answer to the first question is found by examining the column factor weights. The answer to the second question is found by looking at row factor weights. The results given in Table 4 show no single variables being significantly related to more than one common factor and each common factor is defined by a single type of variable. The conclusion is that each common factor represents only one physical effect of the parent material.

The name given to the first common factor in Table 4 is microtexture and is arrived at by the high factor weights on the two particle size variables. The second factor is an expression of moisture transmitting characteristics of the parent material as represented by the two porosity variables. The negative sign has no particular effect on naming of the variable when the analysis is used as an interpretive tool. It means that a factor such as the porosity factor takes the reciprocal name, in this case lack of porosity or massiveness. Factor three represents macrotexture and is defined by the larger particle size variable which also includes the median particle size of the granitic parent material. The fourth common factor is an expression of the effect of parent material depth from the soil surface. The fifth factor relates to mineralogy as described by the high values on the defining variables of quartz and biotite.

Based on the foregoing analyses the specific model selected for hydraulic conductivity of the granitic parent material would be the following:

$$\text{Hydraulic conductivity} = f\,(\text{texture, porosity, depth, and mineralogy})$$

The principal components analysis and varimax factor rotation was undertaken with considerable optimism as a tool for screening the physical factors responsible for hydraulic conductivity of the parent material. Once it was completed it was difficult to see how the analysis aided in the screening process. Numerous research reports and general soils tests have shown that the same general variables produce a similar universal response. Nothing new was gained from the statistical analysis.

As a result of these analyses, the comments of Matalas and Reiher (1967) seem to be applicable to these results. They felt that any factor analysis might well be useful where very little is known about the nature of the observed variates. They also felt that hydrologists have for the most part advanced scientifically beyond this stage. Principal components analysis with varimax factor rotation analysis may be useful in leading the investigator to ask why variables are associated in some factor. However, it should be remembered that deciding on what constitutes a defining variable and assignment of names to common factors is entirely subjective and may lead to biased results.

The principal components analysis and varimax factor rotation analysis are best utilized where a large (greater than 20) number of variables can be analyzed.

Comparison of Field and Laboratory Hydraulic Conductivity

The field and laboratory data were used to determine if a relationship existed between the two measurements. A simple comparison was made to determine if laboratory methods could be used to characterize permeability of the parent material in place of the laborious and time consuming field measurements. The simple correlation analysis shown in Table 3 indicates no significant correlation between the two measurements.

The results do not indicate which technique is the more suitable and, since the physical parameters apply to both samples, additional statistical analysis would yield no better results than that of the simple correlation analysis. However, each technique is a useful tool. The double ring method has values as a qualitative measurement of site conditions. The infiltrometer has the disadvantage that it is not possible to interpret from the results the nature of the soil profile as related to zones of high and low hydraulic conductivity.

The results of this study show the average field hydraulic conductivity value (1.11 inches per hour) to be greater than that for the saturated laboratory cores (0.99 inches per hour). This difference is assumed to result from the infiltrometer's inability to reflect zones of high and low conductivity. Infiltrometers normally tend to overestimate hydraulic conductivities when initial moisture values are low at time of field sampling because moisture inflow is recharging a dry permeable strata (Erie, 1962).

Laboratory core hydraulic conductivity measurements, on the other hand, seem to be a better parameter for establishing zones of reduced permeability. Through their analysis, hydraulic conductivity measurements assist materially in establishing a cause for resulting permeability values (Perrier and Johnson, 1963). Undisturbed cores are not affected by moisture front movement and measurement problems associated with field data collection. The hydraulic conductivities of undisturbed core samples are useful indices for determining the permeability of the granitic parent material.

Validity of Darcy's Equation for Hydraulic Conductivity Computations

Several authors (Scheidegger, 1960; Todd, 1959; Whipkey, 1966; Wenzel, 1942) show that the Darcy equation is not applicable where high hydraulic gradients produce turbulent flow. Reynolds numbers were computed for the samples with the 12 largest flow velocities to determine if laminar or turbulent flow predominates during saturated moisture movement.

The results of the Reynolds number calculations are shown in Table 5. The highest velocity measured from the undisturbed cores resulted in a Reynolds number of 0.22. Laminar flow predominates only for very low velocities of flow (Wenzel, 1942). Comparing the 12 maximum Reynolds numbers values with the graph of frictional forces given by Todd (1959, p. 49), shows that all the values were

Table 5. Reynolds number calculations for the 12 highest flow velocities.

Sample Number	Reynolds Numbers: Based Upon Average Particle Size	Reynolds Numbers: Based Upon Average Pore Diameter
28	0.22	.0024
29	0.16	.0022
21	0.14	.0021
27	0.11	.0024
39	0.026	.0013
19	0.045	.0009
24	0.035	.0009
22	0.043	.0009
23	0.040	.0014
30	0.018	.0008
31	0.029	.0007
3	0.025	.0007
Average for all 52 core samples	0.0219	0.0006

well within the laminar flow range (N_r less than 1.0). Hence, the use of the Darcy equation for saturated flow is valid for this study.

The Reynolds number calculations using average grain size should be considered as representing a range of values rather than a unique value (Todd, 1959). The average grain diameter covers a wide range of sizes, shapes and packing arrangements. The original use of the Reynolds number criteria utilized the average pore diameter. A pore size distribution was calculated for this study to be used in a later section. Reynolds numbers for the same 12 velocities were calculated using the average pore size of all the core samples. The results from the two types of calculations differ by a factor of over one hundred. The variation between the two calculations would cause definite interpretation problems if the hydraulic conductivities were closer to the turbulent range (N_r greater than one). From this comparison, it is easy to understand why Scheidegger (1960) places little confidence in the Reynolds number concept. The average grain diameter overestimates the resistance forces for the granitic parent material and may tend to yield calculated results in the turbulent range when, in fact, they may be non-turbulent.

Moisture-Suction Curve

An objective of this study was to derive a moisture-suction curve from which a pore size distribution could be calculated.

A simple correlation analysis of the 60 centimeter, 1/3 atmosphere and 15 atmosphere data failed to indicate any significant relationship between the geologic type, depth of sampling, and the physical measurements used to define the parent material (Appendix C, Table D). The conclusion drawn from this analysis was that there was no significant difference between the core samples by depth and the parent material. Therefore, the moisture-suction results were used as simple mean values.

Moisture contents shown in Table 6 are average moisture content for the stated suction points. The average moisture values were used to plot the moisture-suction curve shown in Figure 9. Lack of extreme variability can be seen by comparing the moisture contents at 2.5 and 5.5 foot depths (see Table 6).

The moisture-suction curves shown in Figure 9 represent the average surface and parent material moisture contents. The moisture values were used to determine subsequent pore size distributions. Surface soil data are presented to show that surface soils do not restrict moisture movement to lower depths.

Surface soil moisture data were obtained from Rowe and Colman (1951). The most noticeable characteristic of the curve is the small difference in moisture contents between the surface soil and parent material. Soils developed in arid zones most closely reflect the character of the parent material (Maxey, 1964). Storey (1948) states that the soil correlates quite closely with the geology of the San Gabriel Mountains and in most cases consists of physically disintegrated parent rock. The granitic parent material type underlies about 48 percent of the San Gabriel Mountains. The inference which

Table 6. Average moisture storage values for the granitic parent material.

Depth Below Surface (feet)	Bulk Density	Moisture Content Percent by Volume		
		60 cm.	1/3 atm.	15 atm.
2.5	1.58	23.9	14.1	3.3
3.0	1.58	24.5	14.5	3.3
3.5	1.67	20.5	12.2	5.0
4.0	1.67	23.2	13.7	4.7
4.5	1.78	22.1	13.0	3.0
5.0	1.67	20.7	12.2	2.3
5.5	1.86	20.1	11.9	3.3
Average	1.68	22.1	13.1	3.6
	Surface soil data (Rowe and Colman, 1951)			
Average	1.66	25.6	16.3	5.6

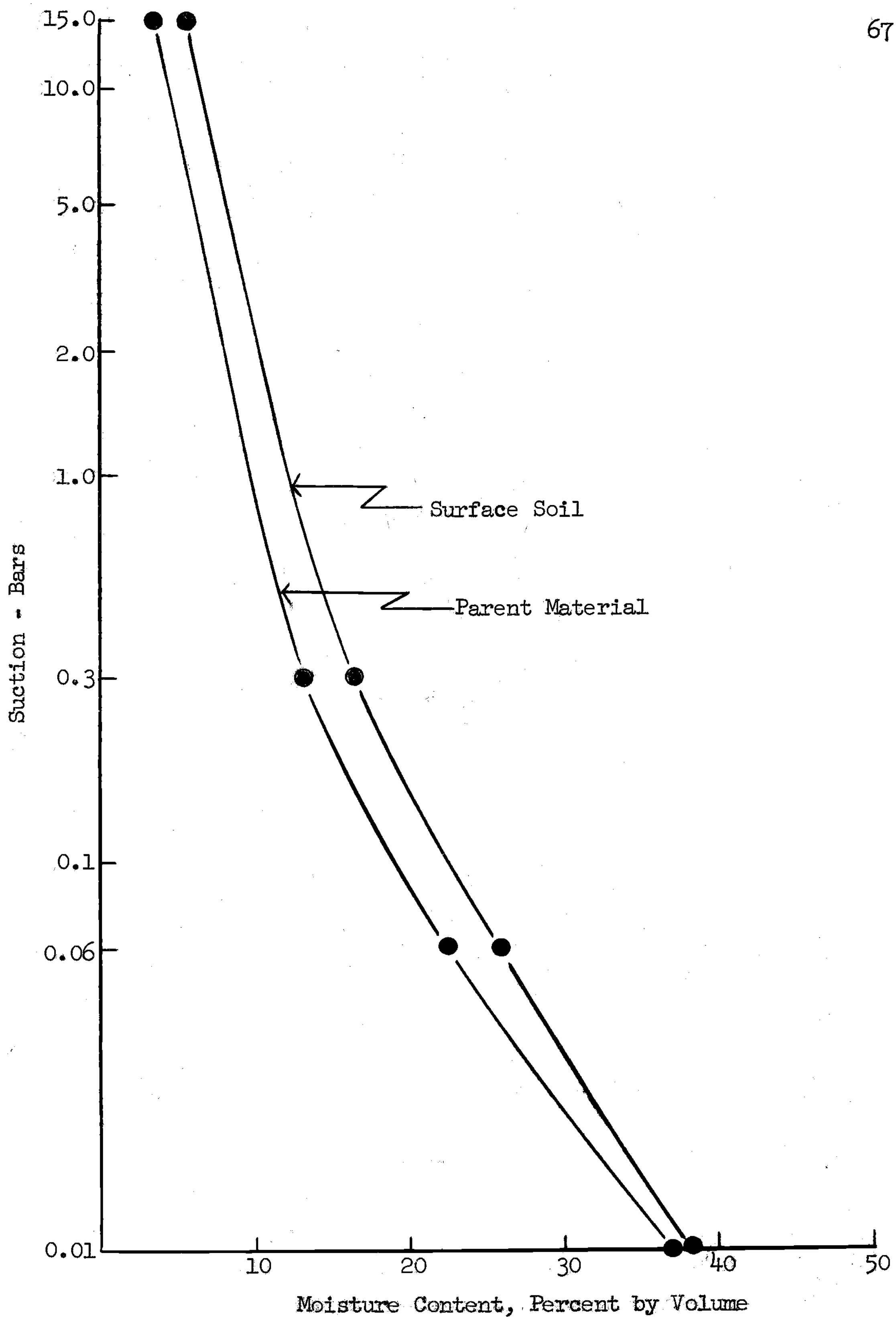


Figure 9. Moisture-suction curve for the surface soil and granitic parent material.

can be drawn from the moisture-suction curves is that the surface soil and parent material moisture characteristics are very similar. The similarity results from the fact that the soil is physically disintegrated granitic parent material.

Pore Size Distribution

The moisture-suction curves are indicative of the pore size distribution of the surface soil and parent material. The distribution of pores and their relative size has important hydrologic significance. Earlier non-capillary porosity was shown to be significantly related to saturated hydraulic conductivity. Thus, non-capillary porosity and moisture storage are governed by the size and distribution of pores which in turn govern the movement of moisture within a profile.

Results of the pore size calculations are shown in Table 7. The approximate pore radii were obtained by substituting moisture suction values into the capillary rise equation. The distribution of pore space associated with each size class is also presented.

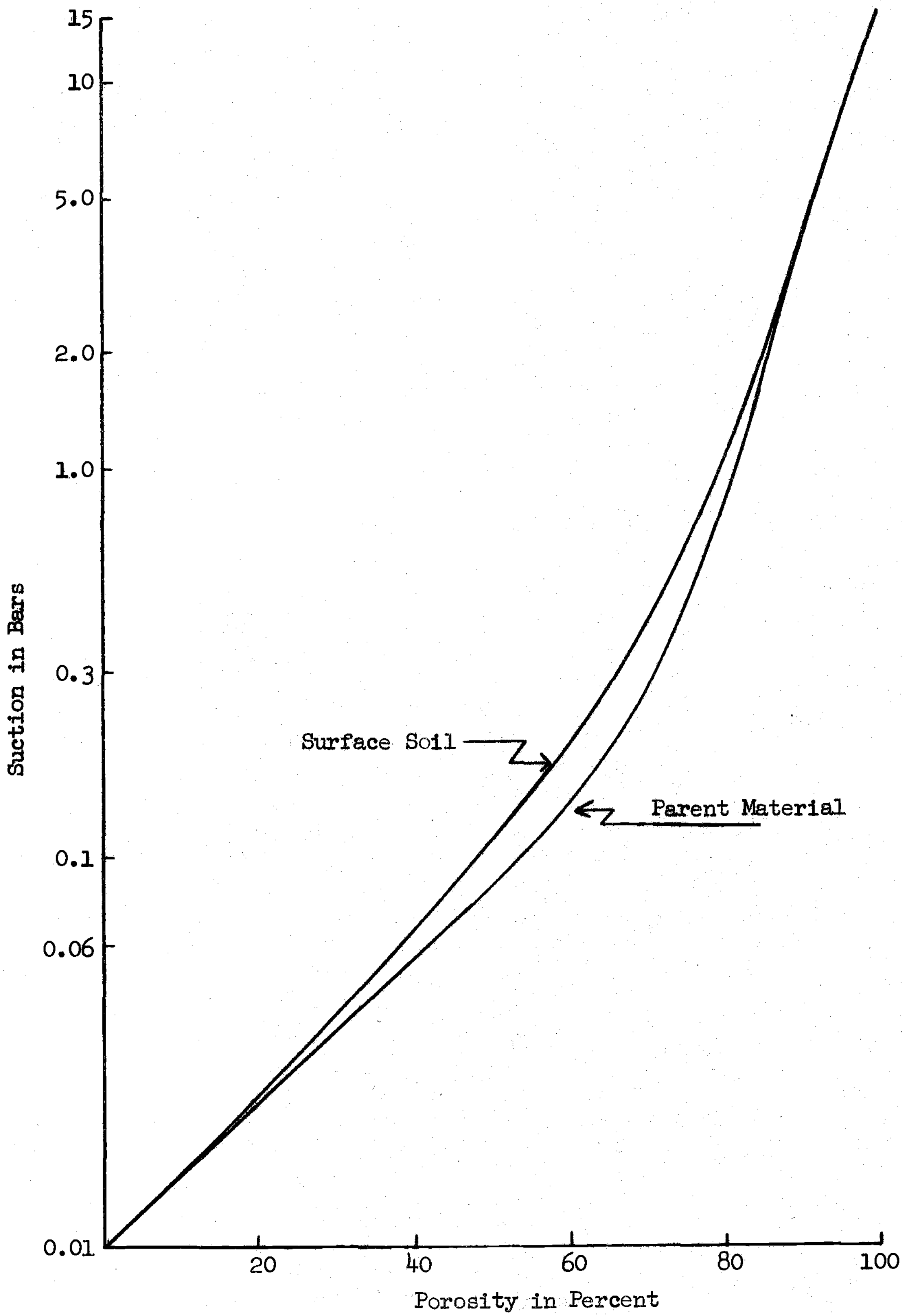
The pore size distribution curve (Figure 10) shows that approximately 71 percent of the pores in the parent material and 67 percent of the soil pores are non-capillary in size and are drained under the influence of gravity.

The data of the moisture-suction curves and pore size distribution curves indicate three important hydrologic factors. First, the average hydraulic conductivity of the surface soil (1.31 inches

Table 7. Average pore sizes and their distribution within the profile.

Suction Pressure (bars)	Pore Sizes (centimeters)	Pore Spaces Rock (percent)	Pore Spaces Soil (percent)	Distribution Rock (percent)	Distribution Soil (percent)
0.06	247.89×10^{-5}	14.8	12.5	44.2	38.5
0.10	148.73×10^{-5}	3.4	3.3	10.1	10.2
0.30	49.58×10^{-5}	5.6	6.0	16.7	18.5
1.00	14.78×10^{-5}	3.7	4.3	11.0	13.1
2.00	7.44×10^{-5}	1.5	1.8	4.5	5.4
5.00	2.97×10^{-5}	1.8	2.1	5.4	6.4
10.00	1.47×10^{-5}	1.5	1.7	4.5	5.1
15.00	9.92×10^{-6}	1.2	0.9	3.6	2.8

Figure 10. Pore size distribution curve of the surface and parent material.


15
10
5.0
2.0
1.0
0.3
0.1
0.06
0.01
Suction in Bars
Surface Soil
Parent Material
20
40
60
80
100
Porosity in Percent

per hour) and parent material (0.99 inches per hour) within the first six feet is very high and indicates that moisture is transmitted readily. Second, on the average there is a large detention storage capacity. The detention storage is 2.6 inches (21.8 percent porosity between complete saturation and 1/3 atmosphere X 12 inches soil depth) and 2.9 inches per foot of depth for the surface soil and parent material respectively. The large detention storage value implies that precipitation greater than 2.6 inches is necessary to fully saturate the profile before surface runoff would occur. Third, there is a high retention storage capacity to be satisfied before moisture is able to move readily to lower depths. The retention storage for the surface soil is 1.4 inches per foot of depth and for the parent material is 1.1 inches per foot of rock depth. These results are thought to be the important factors for interpreting surface runoff conditions and subsurface flow problems.

From the three points stated it appears that often the ability of these mountain areas to absorb and store moisture is greatly underestimated. This ability to retain large quantities of moisture within the basin greatly lengthens the time of concentration. Stafford and Troxell (1944) reported that 52 inches of a 60 inch rainfall year were absorbed by the soil and parent material of one watershed in the San Bernardino Mountains, a geologic formation similar in soil and parent material to the study area.

HYDROLOGIC INTERPRETATION

Most frequently when overland flow occurs on the soils of a watershed it is because of rainfall intensities in excess of either the soil's infiltration capacity or the saturated hydraulic conductivity of the least permeable stratum in the soil profile. Overland flow is defined as the flow of rainwater over the land surface toward the stream channel. When rain falls at a rate less than the saturated hydraulic conductivity, the soil and parent material are able to store or transmit moisture at a rate which could eliminate overland flow. The results of the permeability measurements made during this study indicate that water movement through the surface soil and granitic parent material should be fairly rapid during any storm. It is hypothesized that overland flow is not an important hydrologic parameter contributing to flood runoff. The pore size distribution shows that a large detention storage volume must be satisfied before overland flow can result from a saturated mantle. These high permeabilities and high percentage of non-capillary pores cause the questions to be asked: Does saturated flow ever develop under conditions of prolonged rainfall and produce overland flow? If so, is the volume of runoff produced sufficient to cause major flooding? In part, the answer to those questions may be found by analyzing rainfall hyetographs and streamflow hydrographs. If the parent material is restricting moisture movement and causing soil saturation and subsequent overland flow then flooding would occur when rainfall intensities exceed its ability to transmit water and are of long enough duration to satisfy any moisture deficits.

Significance of Permeability Measurements in Determining Overland Flow

The soil and parent material of the study area are typical of the parent material underlying about 48 percent of the San Gabriel Mountains. It should be possible then to apply the findings of this study to the San Gabriel Mountain watersheds.

In order to evaluate overland flow it was assumed that: (1) rains falling in the early storms of the year serve only to satisfy retention storage, (2) the amount of rain falling at rates in excess of the soils hydraulic conductivity contributes to overland flow and, (3) the amount of rain falling at rates greater than the parent material hydraulic conductivity results in overland flow.

Bentley's (1961) data shows that 74 percent of the Experimental Forest is covered by soils two feet or less in depth (Table 8). A two foot soil profile, underlain by parent material which possesses the average characteristics of the core samples, was assumed for testing the hypothesis. The average hydraulic conductivity of the surface soil and parent material used was 1.31 and 0.99 inches per hour, respectively.

Table 8. Percent of acreage on the San Dimas Experimental Forest, by slope gradient and soil depth classes (Bentley, 1961).

Steepness of Slope	Dominant Depth of Soil					
	Very shallow	Shallow	Medium	Deep		All depths
	Under 1 foot	1 to 2 feet	2 to 3 feet	3 to 4 feet	Over 4 feet	
	percent					
Moderate to steep under 40[1]	--	2	3	1	1	7
Steep 40 - 55[1]	[2]	2	3	1	[2]	7
Very steep 55 - 70[1]	4	23	12	3	[2]	42
Extremely steep over 70[1]	34	9	1	--	--	44
All gradients	38	36	19	5	2	100

[1] Slope gradient, in percent

[2] Less than 1 percent of the acreage

Use of Available Storm Rainfall

The first screening of rainfall records was to use total storm rainfall and 24 hour duration rainfall, a source of data readily available to hydrologists. Total storm rainfall and 24 hour duration rainfall were used in conjunction with a two foot profile, without regard for rainfall intensity, to evaluate storm size as a source of information that might identify an overland flow producing storm. A total of 460 storms were available for screening. Of the 460 storms, there were 49 storms that could possibly produce overland flow from a saturated watershed. In order to saturate a two foot soil profile from an air-dry state it would take more than 8.1 inches of rainfall (assuming 32.4 percent void space, 2 feet of soil and 10 percent interception losses). The annual series (Appendix A, Figure A) for total storm precipitation shows that storms in excess of 8 inches are equalled or exceeded 25 percent of the time which means that one year out of four will have at least one storm greater than 8 inches.

If a storm is assumed to fall on a watershed where the soils are at field capacity, more than 6.0 inches are needed to fully saturate the soil (assuming 21.8 percent void space, 2 foot deep soil and 10 percent interception loss). If complete saturation was the only criterion for producing overland flow, a 6 inch storm then would be the smallest storm under which any conceivable set of circumstances could produce overland flow. The annual series for 24 hour storm intensity (Appendix A, Figure A) indicates that such a storm would be equalled or exceeded about once every four and one-half years.

In spite of the fact that total storm rainfall and 24 hour duration data are readily available and often used by hydrologists as a flood hydrology variable, it was not very useful for this study. The use of these data did, however, give some indication as to the size of storm that might produce overland flow. The data were limiting because of the fact that drainage occurs during storms, rainfall is not always falling at the same intensity, and total recorded storm rainfall may be spread over several days.

The high permeability of the soil and parent material indicates that amount and distribution of storm rainfall in addition to a storage parameter should be used to evaluate the presence or absence of overland flow from the small steep watersheds of the San Gabriel Mountains.

Test Watershed

In order to evaluate overland flow from small steep watersheds, Monroe Canyon, an 875 acre watershed on the Experimental Forest, was chosen for the study because it has a good streamflow record. Surface soil data reported earlier in this study were collected from Monroe Canyon and reported by Rowe and Colman (1951). The vegetation is representative of that found in the chaparral zone and had not been burned in more than 40 years. The geology and soils are typical of much of the San Gabriel Mountains and representative of the granitic parent material of this study.

Routing Infiltrated Moisture

The soil and parent material moisture storage for Monroe Canyon was handled in the following manner. A soil depth of two feet with a detention storage capacity of 2.6 inches per foot of depth was assumed. A four foot deep granitic parent material with a detention storage capacity of 2.9 inches per foot of depth was used. Any storms producing overland flow were assumed to fall on the Monroe Canyon watershed when retention-storage requirements were already satisfied. The soil is nonlimiting because it has a higher permeability than the parent material.

The amount of rain falling on the soil surface was budgeted into the soil and parent material according to the respective permeabilities and storage capacities of those two strata. Outflow from the two foot soil profile into the parent material was considered to start only after detention storage was satisfied. The budgeting of overland flow can be expressed by the following equation:

$$\text{Overland flow} = \text{Intensity} - 1.31''/\text{hr. when soil storage} < 5.2'' \quad (1)$$

$$\text{Overland flow} = \text{Intensity} - 0.99''/\text{hr. when soil storage} > 5.2'' \quad (2)$$

where:

1.31"/hr. = saturated hydraulic conductivity of the soil

5.2" = detention storage capacity of a 2 foot soil profile

0.99"/hr. = saturated hydraulic conductivity of the parent material

This calculation was made for the rain falling during each six minute period throughout a storm.

If rain fell at a rate greater than the saturated hydraulic conductivity of the soil the difference was considered to be overland flow (Equation 1). Any rain falling at less than that rate was assumed to enter the system and satisfy detention storage or move into the parent material. If rain fell at a rate greater than the permeability of the parent material after soil detention storage was already satisfied, the excess amount was considered to be overland flow (Equation 2). If rain fell at a rate less than the permeability of the parent material it was assumed to be stored.

Rainfall Intensity Distribution

A total of 29 storms (1933 to 1958) falling on Monroe Canyon were tallied that had some portion of the precipitation falling at a rate greater than 1.0 inch per hour during a six minute time period. A six minute interval is about the limit of accuracy for reading raingage charts. Table 9 lists the storms and shows the percent of precipitation falling at rates greater than the specified intensity. The storm numbers refer to the numbering system used by Reimann and Hamilton (1959).

The percentages in Table 9 were obtained from raingage records which had been digitized and then interpreted and summarized on an IBM model 1620 computer. Using the rainfall intensity program it was possible to inspect every 6 minute rainfall period for intensities in excess of the saturated hydraulic conductivity.

Intensity data from Table 9 indicates that on the average only 13 percent of the storm precipitation fell at rates greater than the permeability of the parent material.

Table 9. Storm record from Monroe Canyon showing percent storm precipitation falling at rates greater than stated intensity.

Storm Number	Intensities in Inches Per Hour 0.2	0.4	1.00	2.00	Storm Total	Duration
	---- percent of total ----				(inches)	(hours)
55*	70.6	44.5	11.1	2.3	4.64	23.5
85*	89.1	75.4	24.4	10.6	12.06	39.0
110*	74.2	32.5	17.4	6.8	5.20	42.0
116*	53.2	32.3	11.5	6.4	5.47	146.2
126	70.8	45.8	12.5	0	1.89	28.0
144	77.2	51.7	22.0	2.0	5.71	129.2
147	64.7	42.1	19.6	2.9	4.02	68.5
164	71.6	30.1	11.3	3.7	2.09	25.7
182*	86.0	71.3	1.8	0	15.24	59.7
186	70.7	44.8	9.0	0	6.06	83.0
187	69.8	40.8	6.5	0	6.65	45.5
209*	69.1	32.1	13.2	3.5	8.94	81.5
220*	77.4	48.3	10.2	4.4	8.34	66.0
241*	75.8	54.3	15.1	7.5	10.94	100.2
247	63.5	34.8	6.2	0	5.08	118.4
256*	77.1	44.5	1.0	0	3.62	19.6
307	74.1	48.3	11.8	4.3	3.66	32.1
346*	62.9	31.1	5.3	0	7.32	81.5
380	71.0	44.2	8.6	2.8	5.43	53.8
381*	67.7	28.9	7.4	1.6	4.76	38.8
382	81.7	48.0	15.3	0	4.09	34.6
387	82.5	55.5	26.9	9.5	2.48	31.6
413*	79.7	43.7	8.1	0	11.06	64.4
426*	70.7	43.8	15.7	2.2	3.50	22.1
446	78.4	52.2	17.6	1.9	6.02	51.6
448	71.9	45.4	20.4	7.5	5.20	59.6
458	81.2	45.8	19.7	0	3.78	33.5
459*	73.1	42.6	10.7	4.6	2.56	36.1
469*	69.5	54.8	10.9	0	3.23	34.4

* Storms used in annual flood series.

Peak Flow Tabulation

The hypothesis concerning the importance of overland flow was further examined by investigating the peak discharges from Monroe Canyon. Table 10 is a tabulation of the annual flood peaks from Monroe Canyon from which a flood recurrence interval was calculated. Figure 11 shows the storm return period. Only six storms produced annual peak flows having a return period of greater than four years. Table 11 lists these six storms along with other information on each storm. The six storms were singled out because they had high stormflow and presented the greatest possibility of containing overland flow.

Several interesting points can be noted from Table 11. Storm number 182 had a peak flow of about the same magnitude as storm 209 but there is a difference in the percent of precipitation falling at a rate in excess of the hydraulic conductivity of the parent material and surface soil. Storm 459 produced a peak flow in the same range as storms 209 and 182 from somewhat less rainfall.

Flood Peak Hydrographs

Storm hydrographs were inspected to determine the nature of the rainfall-runoff relationships. Figures 12, 13, 14, 15, 16, and 17 are the runoff hydrographs for the respective peak flows. Also, plotted are the rainfall hyetographs for each flood peak. Those figures also contain the estimated time when soil and parent material

Table 10. Annual peak flood discharges for Monroe Canyon on the San Dimas Experimental Forest (drainage area = 1.37 sq. mi.).

Water Year	Storm Number	Annual Peak Flood Discharge Q Peak (csm)	Order Number of Peak m	Recurrence Interval $Tr = \frac{n+1}{m} = \frac{26}{m}$
35	34	4.29	17	1.53
36	45	5.56	15	1.73
37	55	20.45	7	3.72
38	85	365.00	1	26.00
39	110	5.69	14	1.86
40	116	8.04	13	2.00
41	146	16.72	8	3.25
42	167	0.72	18	1.44
43	182	66.21	3	8.57
44	209	67.95	2	13.00
45	220	16.07	9	2.89
46	241	31.70	6	4.34
47	256	14.34	11	2.36
48	283	0.25	20	1.30
49	301	0.15	23	1.13
50	315	0.40	19	1.37
51	335	0.12	25	1.04
52	346	32.00	5	5.20
53	362	0.20	21	1.24
54	381	10.90	12	2.16
55	396	0.17	22	1.18
56	413	14.36	10	2.60
57	426	0.13	24	1.08
58	459	65.66	4	6.50
59	469	4.63	16	1.62

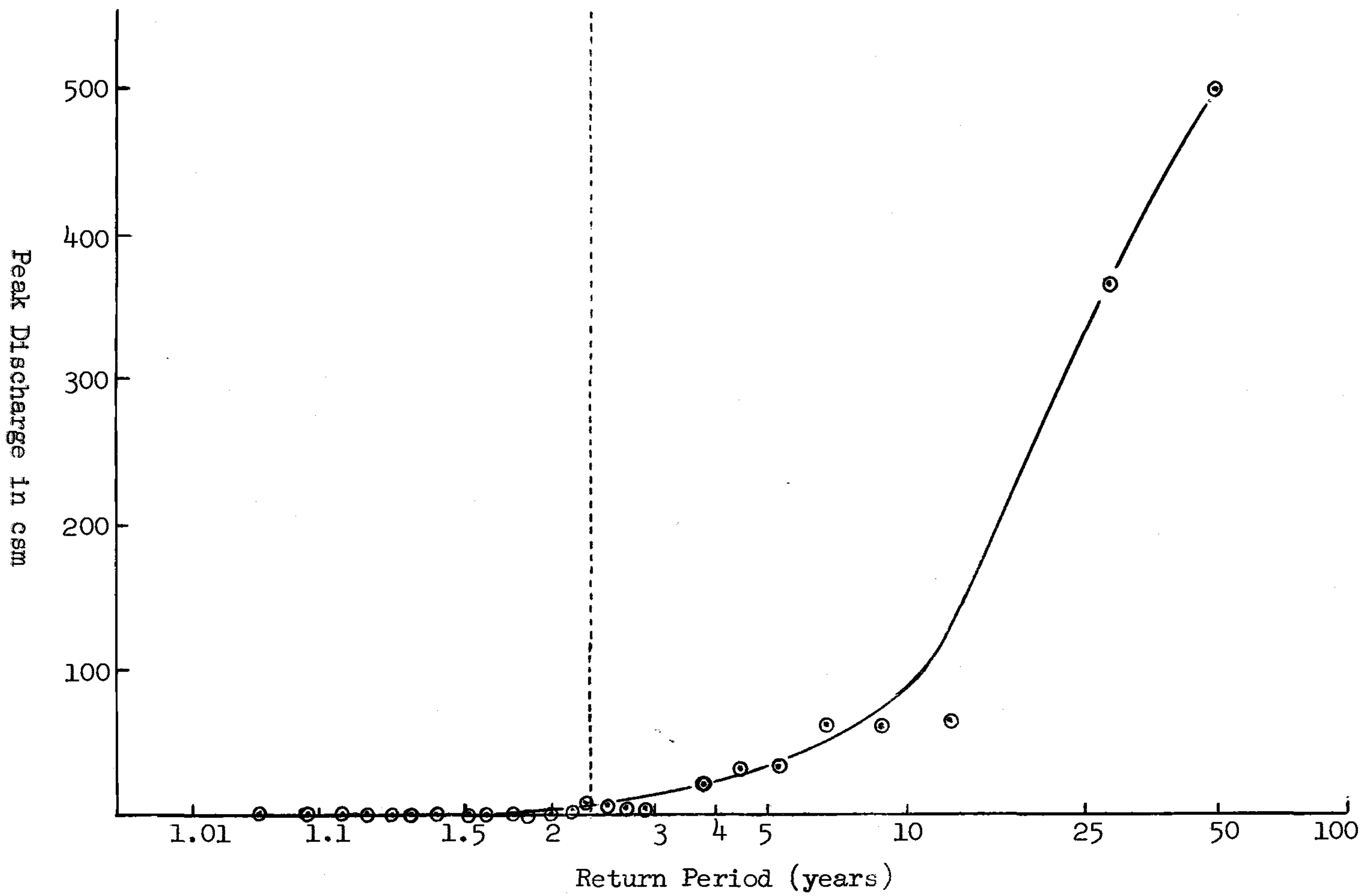


Figure 11. Flood frequency curve for Monroe Canyon on the San Dimas Experimental Forest.

Table 11. Monroe Canyon storm record for storms producing peak flows have a return period of greater than four years.

Order Number	30 Day Antecedent Rainfall	Time Since Last Storm	Storm Length	Total Storm Precip.	Amount of Rainfall > 0.99 in/hr	Amount of Rainfall > 1.31 in/hr	Flood Peak	Storm Runoff	Peak Runoff Rate
	(inches)	(days)	(hours)	(inches)	(inches)	(inches)	(csm)	(inches)	(in/hr)
1 (85)	16.94	8	39.0	12.06	2.94	1.28	365	1/	1/
2 (209)	4.08	2	81.5	8.94	1.18	.94	67.95	.78	.11
3 (182)	1.45	27	59.7	15.24	.27	.01	66.21	1.19	.10
4 (459)	8.77	1	74.5	6.06	.27	.12	65.66	.78	.10
5 (346)	12.31	2	81.5	7.32	.39	.19	32.00	.40	.05
6 (241)	.38	10	100.2	10.94	1.65	1.33	31.70	.24	.05

1/ Record lost due to inundation of gaging station.

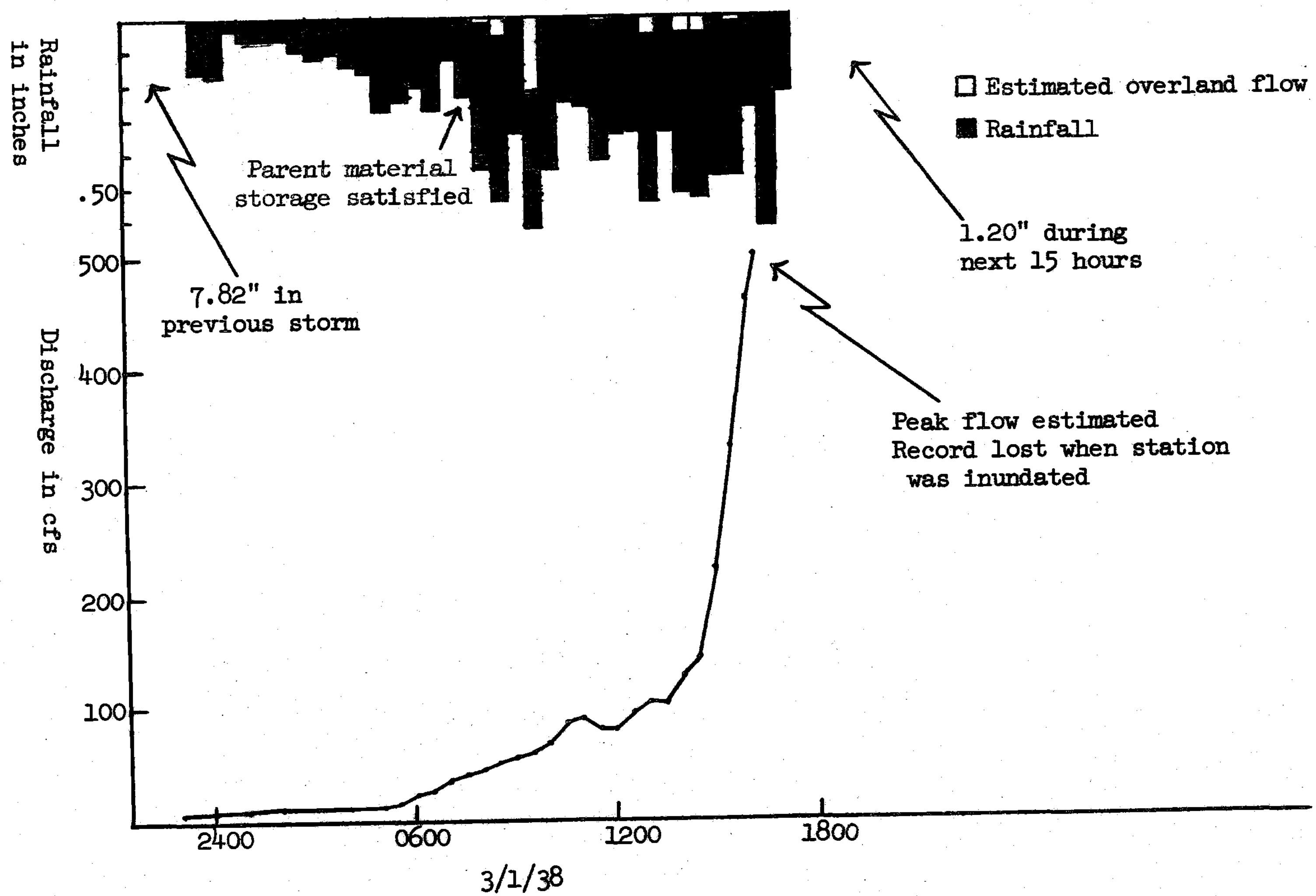


Figure 12. Monroe Canyon flood peak discharge related to storm number 85.

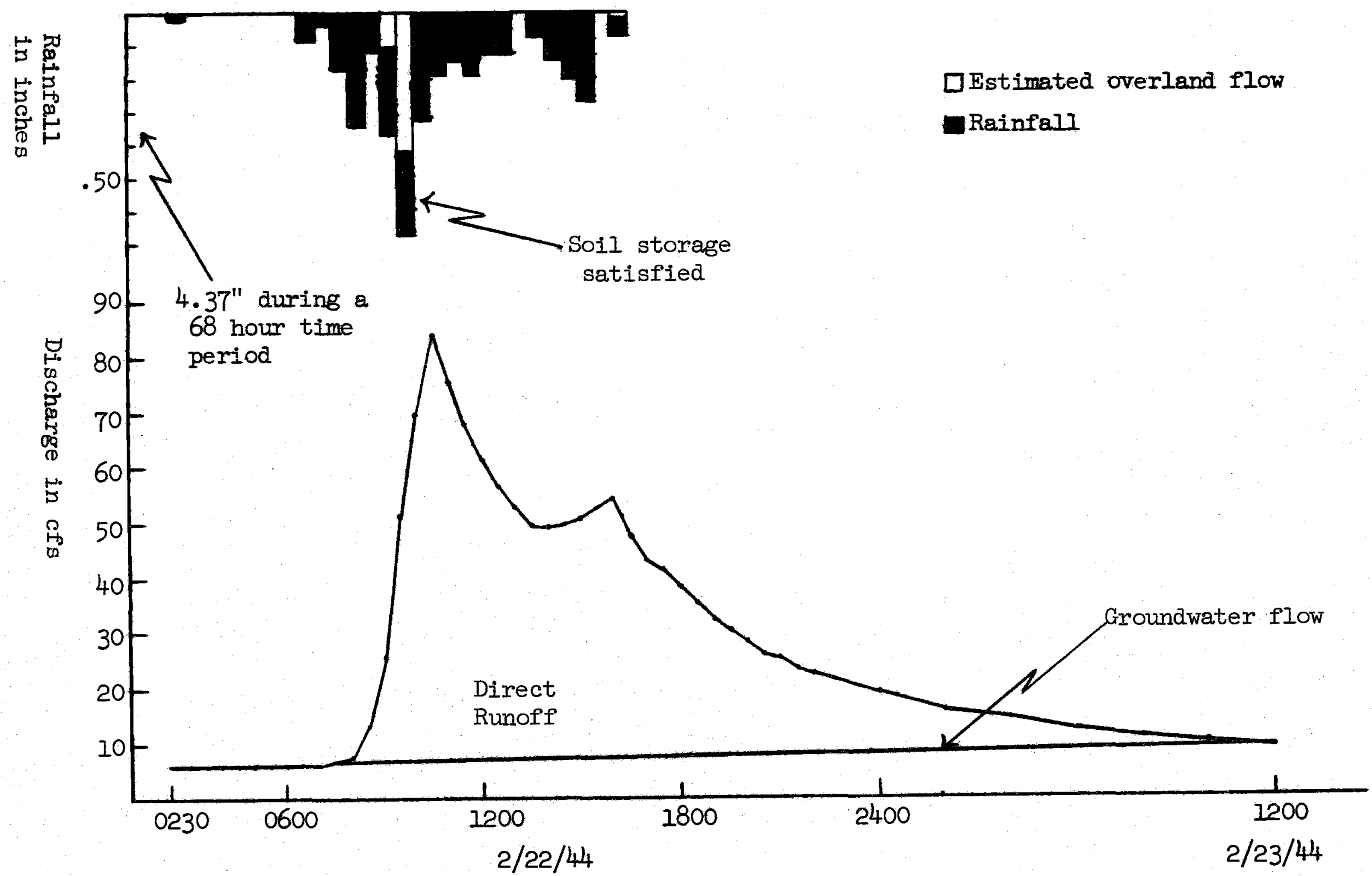


Figure 13. Monroe Canyon flood peak discharge related to storm number 209.

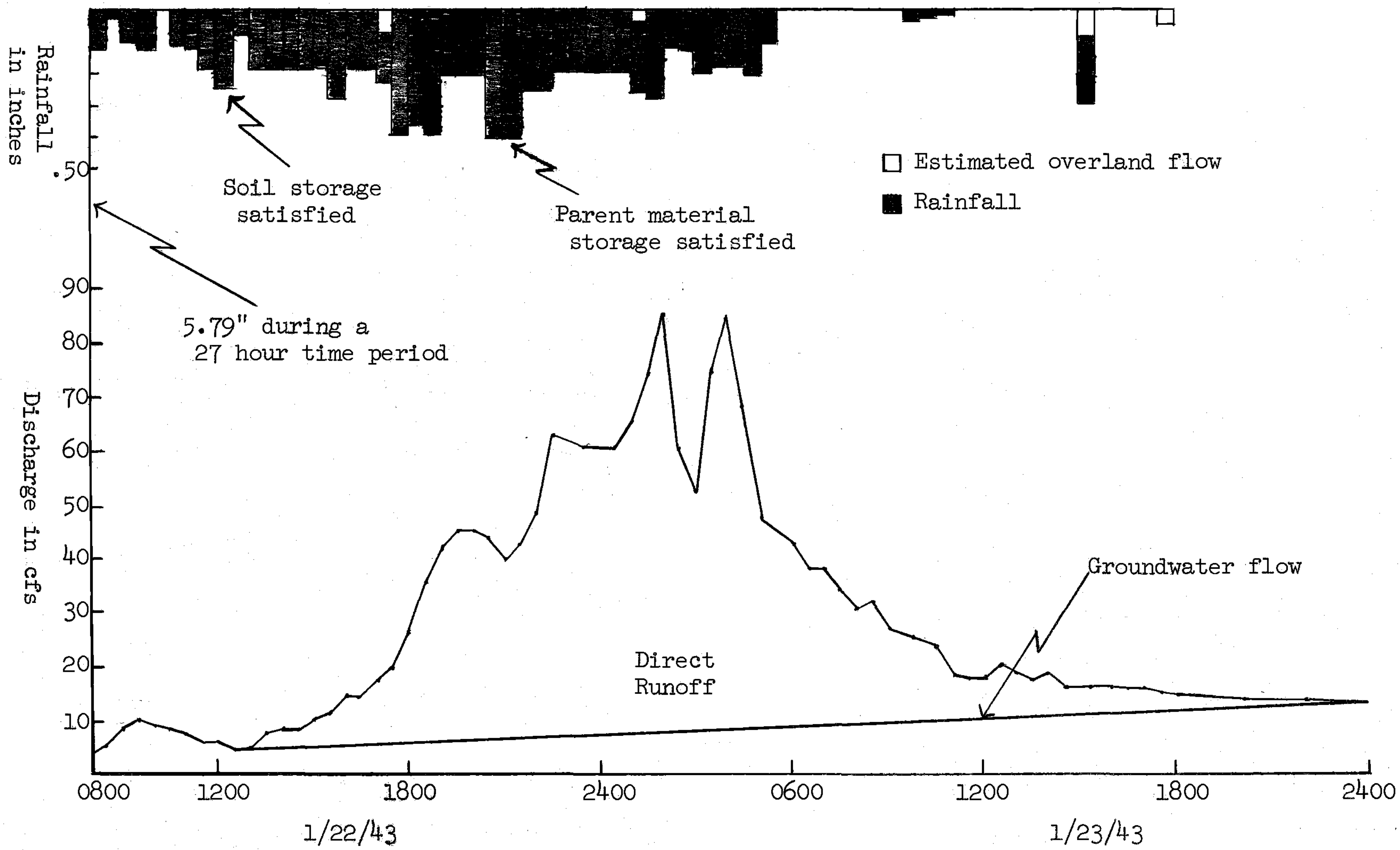


Figure 14. Monroe Canyon flood peak discharge related to storm number 182.

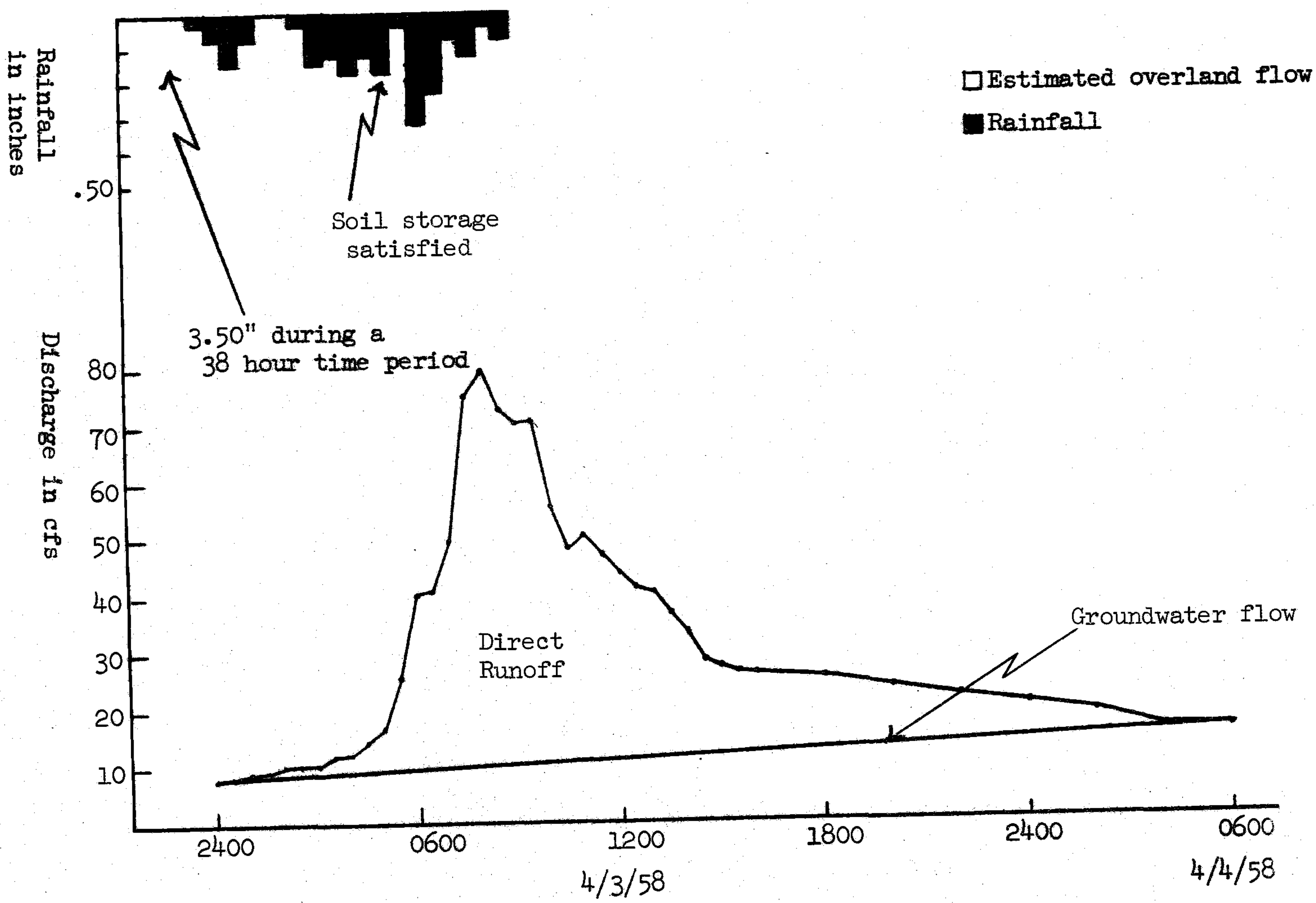


Figure 15. Morroe Canyon flood peak discharge related to storm number 459.

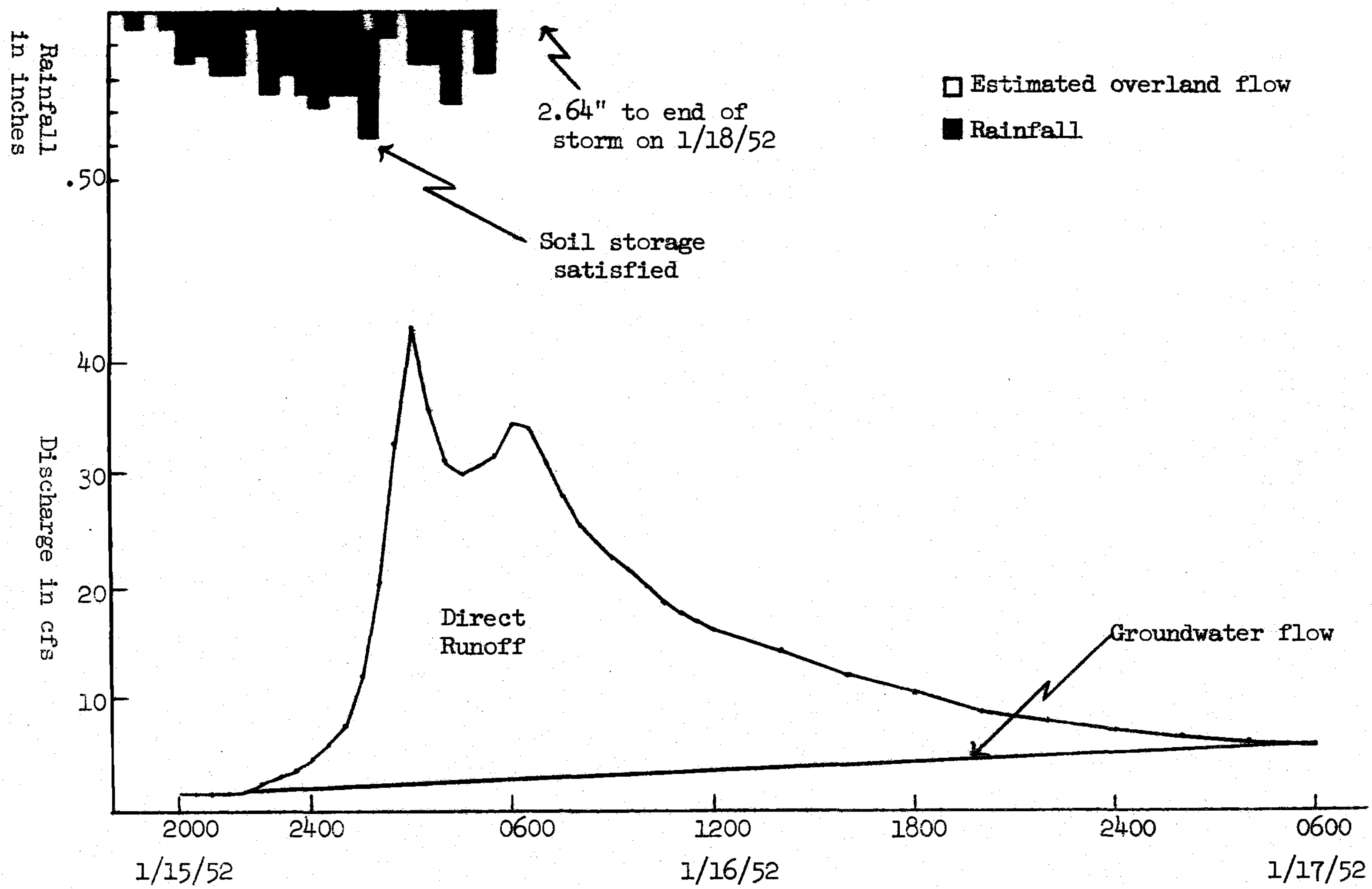


Figure 16. Monroe Canyon flood peak discharge related to storm number 346.

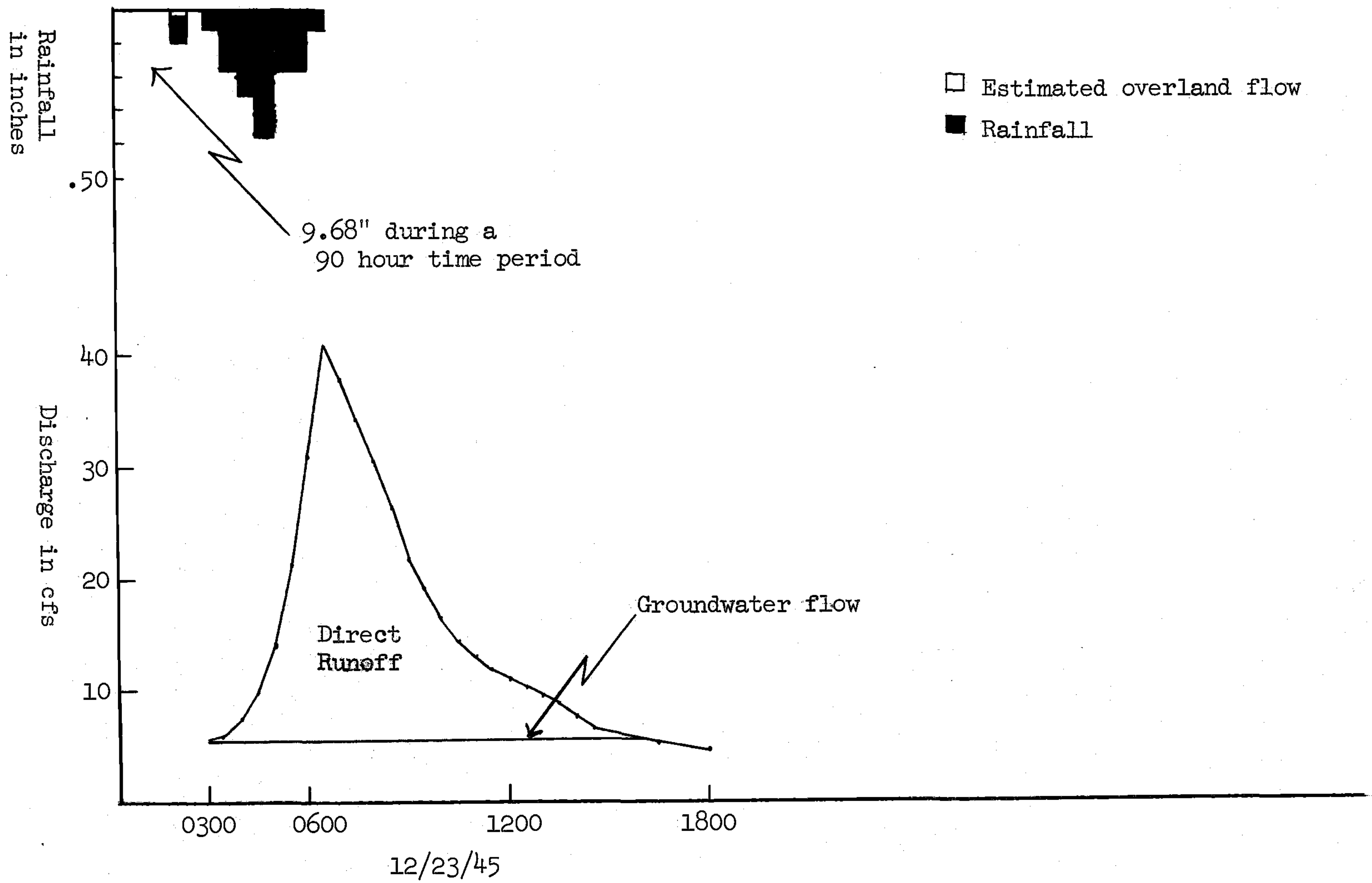


Figure 17. Monroe Canyon flood peak discharge related to storm number 241.

storage requirements were satisfied and the amounts of rainfall that fell at rates greater than the hydraulic conductivities of the soil or parent material. (Note: Six minute time periods were used in assessing the amount of overland flow but the rainfall hyetographs are plotted in half hour intervals.) Overland flow for the time period was estimated by subtracting the amount of water infiltrated from the amount of rainfall during the given intensity period.

The 1938 Flood

Storm number 85 (March 1938) produced the largest flood since 1914. Even though this flood was of considerable magnitude and inundated the low-lying areas of the Los Angeles basin, the observed runoff from study areas on the Experimental Forest were consistent with the hypothesis of little influence of overland flow.

Colman (1951), referring to the 1938 flood, states "Our studies at the San Dimas Experimental Forest showed that during this storm there was almost no surface runoff over the surface of the ground. The record peaks of streamflow came after the soil mantle of our watersheds had filled with water. Then, with continued rain there was a rapid seepage of water underground from the hill soils into the stream channels. It was this seepage water that swelled the streams".

For the same storm (#85), Troxell (1953) reported observations for two small watersheds on the Experimental Forest that were 0.06 and 0.08 square miles in area with sideslopes of about 65 percent, main channel gradients of about 20 percent, and maximum distance of water travel of about 0.4 miles from the divide to the gaging stations. He states that "On the basis of the entire storm period of February 27 - March 4, 1938, precipitation of 20.44 inches on the runoff plots produced a direct runoff of 0.06 to 0.17 inches, or less than one percent of the precipitation. In contrast, the Fern Canyon drainage areas (Note: the runoff plots are within the Fern Canyon watershed) produced a runoff of 3.67 and 8.80 inches during this six day period from a storm precipitation of 23.0 inches. The maximum rate of runoff did not appear at the gaging station until several hours after the occurrence of maximum precipitation rates. The very much greater runoff amounting to 16 to 38 percent of the storm precipitation is further evidence of a substantial groundwater contribution even during the flood-runoff period".

General Observations on Overland Flow

Except for storm 85, the remaining 5 storms contributed less than 22 percent of the precipitation to the stormflow peak. If it were possible to accurately delete groundwater flow, direct channel interception and interflow, the estimated overland flow would be somewhat less than shown on the hyetographs. The greatest percentage of stormflow from all six storms appears to come from sources other than overland flow.

The rainfall hyetographs and streamflow hydrographs indicate that overland flow in Monroe Canyon is of limited occurrence even during flood runoff periods. The streamflow peaks did not appear at the gaging station until at least one hour or longer after the occurrence of maximum precipitation rates. During the latter part of storm 182, the estimated overland flow did not even cause a rise in discharge. Colman (1951) and Troxell (1953) reported similar observations for other unburned watersheds on the Experimental Forest.

The delay in peak runoff cannot be defended on the basis of watershed physiography. The mean flow path in Monroe Canyon is about 1.4 miles. The side slopes average about 70 percent. It is estimated that less than one-half hour is required for overland flow to appear at the gaging station. This estimate is based on a streamflow velocity of 10 feet per second and an average overland flow velocity of 0.25 feet per second.

Due to rapid drainage from this coarse textured profile, storm rainfall prior to the peak runoff is of more importance than any 30 day antecedent rainfall or weighted index of antecedent rainfall preceding the storm. Detention storage is the largest volume to satisfy in the soil and parent material. Breaks between storms longer than 2 days allow the detained moisture to drain from the soil.

The volume of runoff related to the flood peak may or may not include an amount of rainfall falling at a rate greater than the permeability of the soil. Channel interception alone cannot account for the volume of direct runoff. Also, the parent material is permeable enough that overland flow is not often encouraged by it restricting moisture movement. Thus, storm seepage flow from the side slopes rather than direct channel interception or overland flow may be the source of the observed stormflow in Monroe Canyon.

A Potential Cause of Overland Flow in the San Gabriel Mountain Watersheds

The New Years Day flood of 1934 from Pickens Canyon (Kraebel, 1934), more recently floods on the Experimental Forest (Rice et al., 1965), and from other watersheds in the San Gabriel Mountains have been the sources for damaging peak flows. Each of these areas yielded overland flow when storm intensities were not exceeding the permeability of the soil or parent material which was similar to the soil and parent material evaluated in this study. The factor that each of these areas had in common was a recent wildfire. Anderson (1949) showed that forest fires often contribute to high peak discharges and debris production. When the mountain slopes are denuded by fire the magnitude of floods resulting from winter rains may be greatly increased.

Severe floods do not always follow fires in the San Gabriel Mountains. The exception to this rule is during years when the storm intensities are not great enough to produce appreciable surface runoff. Figures 18 and 19 taken from Fern Canyon, a watershed with similar soil and parent material, show very clearly the effects of fire on streamflow reactions (Sinclair and Hamilton, 1954). The hydrographs of Figure 18 indicate that streamflow behavior of the two watersheds was similar before the fire, both as to quantity and reaction time. This similarity was a marked contrast to the extreme difference in streamflow following the fire. Table 12 lists the storm rainfall associated with each hydrograph. The relation of peak

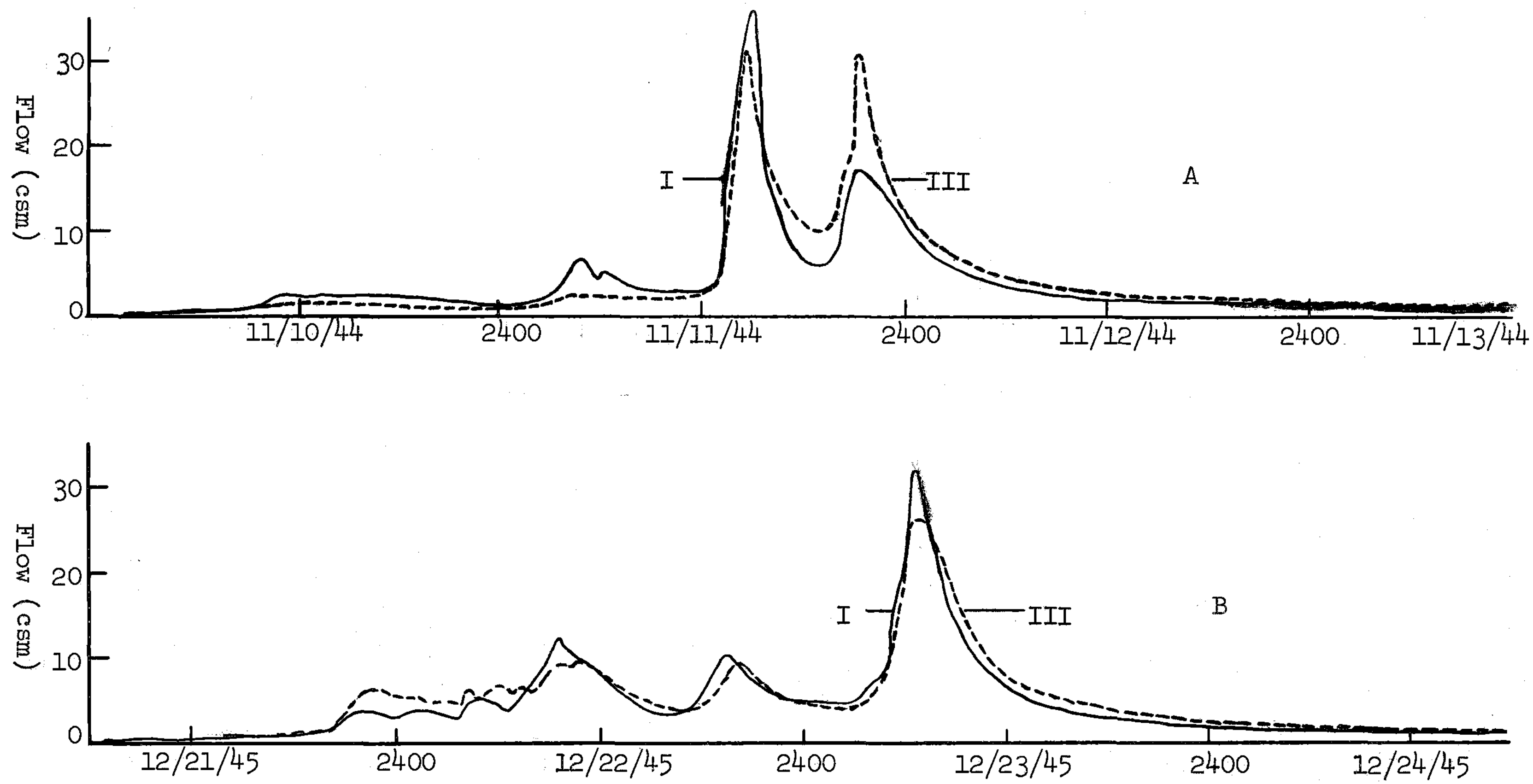


Figure 18. Storm hydrographs for watersheds I and III with watershed vegetation undamaged. A. Storm of November 10-13, 1944. B. Storm of December 21-24, 1945 (Sinclair and Hamilton, 1954).

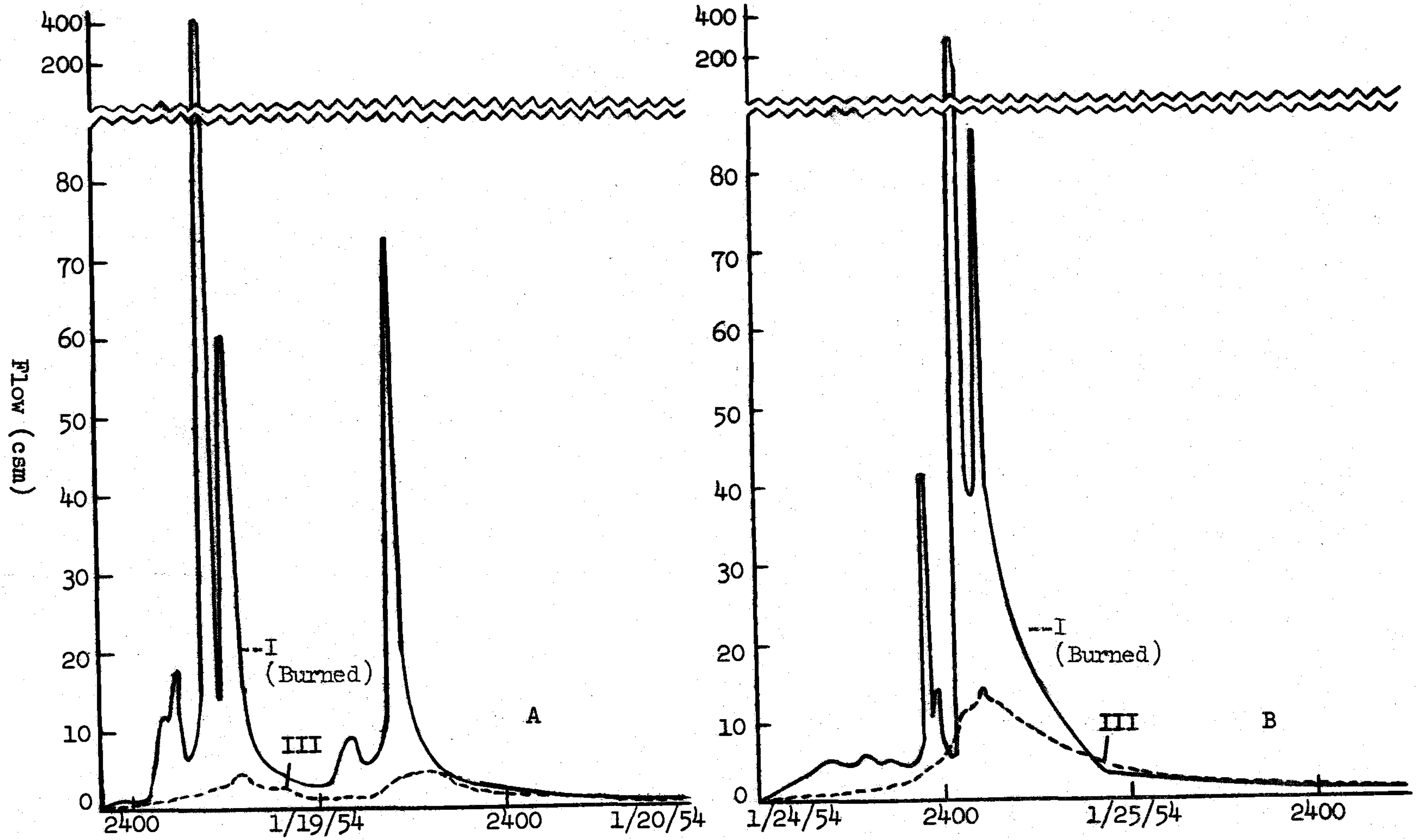


Figure 19. Storm hydrographs for watersheds I and III after 1953 fire. A. Storm of January 18-20, 1954. B. Storm of January 24-25, 1954 (Sinclair and Hamilton, 1954).

Table 12. Watershed I and III rainfall record for stated storms.

Storm Date	30 Day Antecedent Rainfall (inches)	Storm Length (hours)	Total Storm Precip. (inches)	Amount of Rainfall > 0.99 in/hr (inches)	Amount of Rainfall > 2.00 in/hr (inches)	Flood Peak (csm)	Flood Peak (in/hr)
Watershed I (drainage area: 2.38 sq. mi.)(burned during December 1953)							
11/10/44 - 11/13/44	1.28	65.6	9.53	0	0	34.9	.05
12/21/45 - 12/24/45	.35	99.6	11.14	1.18	.19	31.1	.05
1/18/54 - 1/20/54	2.70	54.4	5.98	1.22	.23	429.0	.66
1/24/54 - 1/25/54	8.68	37.4	6.15	1.81	.74	300.0	.46
Watershed III (drainage area: 2.14 sq. mi.)							
11/10/44 - 11/13/44	1.36	66.0	11.61	2.39	.86	31.4	.05
12/21/45 - 12/24/45	.41	100.9	11.06	1.73	.01	29.6	.05
1/18/54 - 1/20/54	2.65	54.3	7.21	.71	.08	14.2	.02
1/24/54 - 1/25/54	9.26	38.5	4.82	.12	0	2.1	<.01

flow between the two watersheds, which had been fairly constant before the fire, was upset. Peak flows during one post-fire storm reached a maximum of 128 times greater than expected from that of the unburned condition, but the amount of rainfall in excess of 1.0 inch per hour is not much different than for the preburn condition.

A recent survey of burned watersheds at the Experimental Forest and nearby areas indicated a "hard-to-wet" surface soil layer (Krammes and DeBano, 1965). A wildfire seemingly does not alter the porosity or storage capacity of the soil or parent material. Heat from the fire is shown to account for extreme water repellency following wildfires in the chaparral zone (DeBano and Krammes, 1966; DeBano, 1966). In short, the permeability of the surface soil is changed. This observation is verified by the fact that during both post-fire storms, the flood peaks from the unburned watershed were from 2 to 2-1/2 hours later than the peaks from the burned watershed (Figure 19). Apparently, the saturated hydraulic conductivity of the soil cannot be reached because a barrier to infiltration has been created within the first few inches of soil.

SUMMARY OF CONCLUSIONS

A study conducted on the San Dimas Experimental Forest in southern California evaluated several physical parameters of saturated moisture movement through the deeply weathered granitic parent material and how those parameters may relate to surface runoff problems.

The physical properties of the granitic parent material investigated in this study are useful for interpreting overland flow from the San Gabriel Mountain watersheds. A factor analysis indicated that the information from 19 descriptive variables could be attributed to 5 common factors. The common factors were micro- and macro-texture, porosity, depth from the surface, and mineralogy. These 5 common factors indicate the types of variables that would be most useful in describing parent material.

No relationship was found to exist between field hydraulic conductivity and laboratory hydraulic conductivity measurements. It was thought that the field technique had value as a qualitative measurement of permeability but was not reliable for establishing quantitative values for subsoil performance under the conditions studied. The laboratory core method appears to provide a better tool for identifying zones of reduced permeability. The cores permit inspection of varying permeabilities with depth. However, the data are not directly applicable unless the variability of the parent material is established.

The Darcy equation was assumed to be a valid model for computation of hydraulic conductivities. The resulting computations, utilizing Reynolds number criterion, yielded values which were well within the laminar flow range. Hence, the use of Darcy's equation for saturated flow was a valid assumption. The results indicate greater than a 100 fold difference between Reynolds numbers calculated using average grain size and average pore diameter and concludes that coarse textured material average grain size overestimates Reynolds numbers.

The importance of the parent material, as it influences overland flow, was evaluated utilizing existing rainfall records, streamflow hydrographs, moisture storage values and the permeability results of this study. Total storm and 24 hour rainfall data were not very useful for evaluating the presence or absence of overland flow. Rainfall was budgeted into the soil and parent material according to the respective permeabilities and storage capacities of those two strata. Overland flow was computed by subtracting the amount of water infiltered from the amount of rain falling during a six minute time period. Rainfall hyetographs and streamflow hydrographs indicated that overland flow is of limited occurrence even during flood runoff periods. Flood peaks were thought to be the result of storm seepage flow from the side slopes rather than from direct channel interception or overland flow.

Floods producing overland flow have occurred in the area but are thought to be the result of a water repellent surface soil created by wildfire temperatures.

RECOMMENDATIONS FOR FUTURE STUDIES

The most important finding of this study relates to the generally accepted concept that overland flow is a frequent occurrence. This study indicates that overland flow from a saturated or unsaturated mantle does not occur very often. Normal stormflow in the San Gabriel Mountains appears to come from storm seepage.

An attempt should be made to verify the findings of this study in areas of different topography and parent material. If they are not caused by a rare set of circumstances, considerable rethinking is in order concerning the mechanism of flood runoff. For example, since overland flow does not seem to be the immediate cause of flood peaks, research should be directed toward understanding lateral subsurface moisture movement.

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APPENDICES

APPENDIX A

RAINFALL DISTRIBUTION CURVES

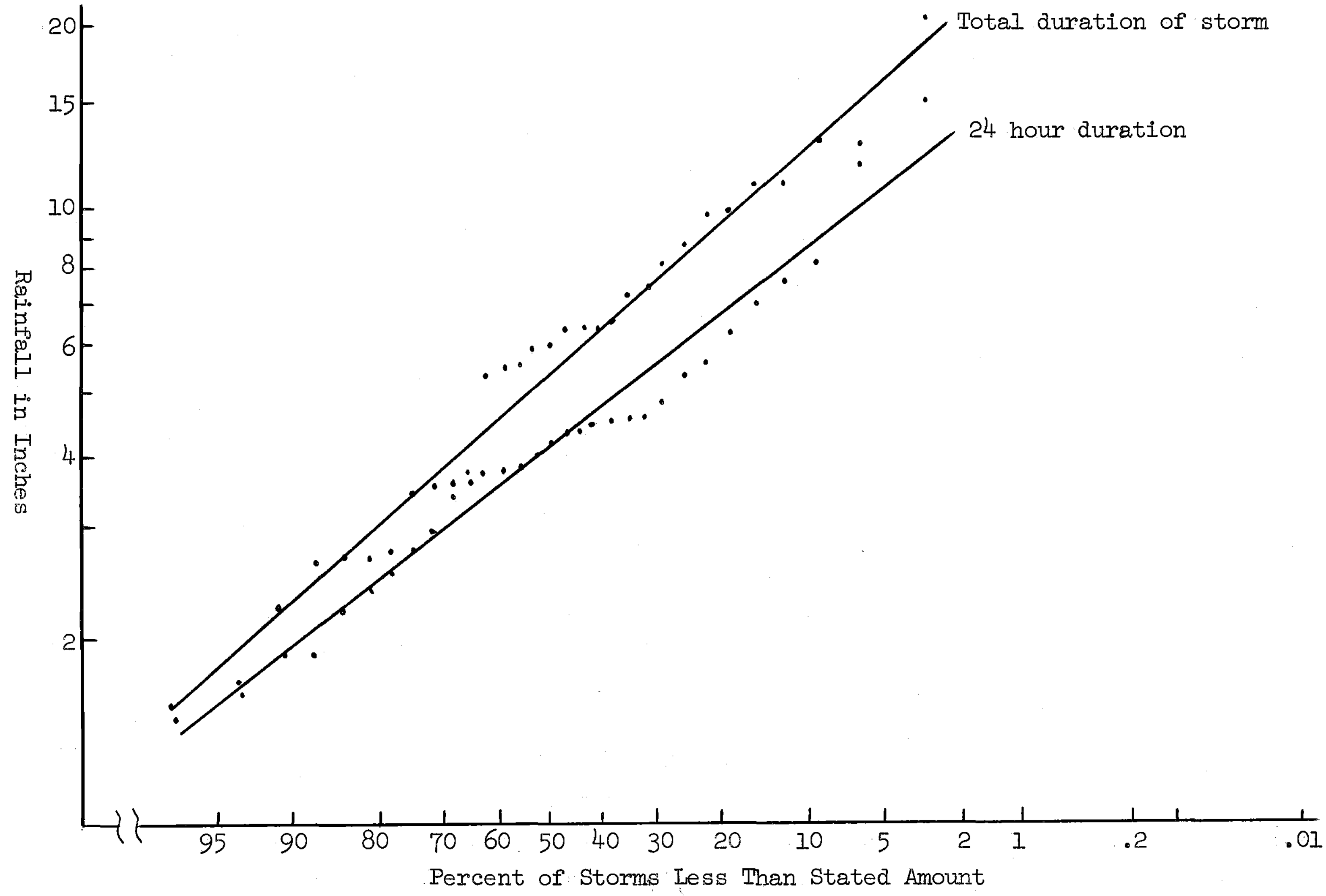

Figure A. Annual series of total storm amount and 24 hour intensity rainfall data.

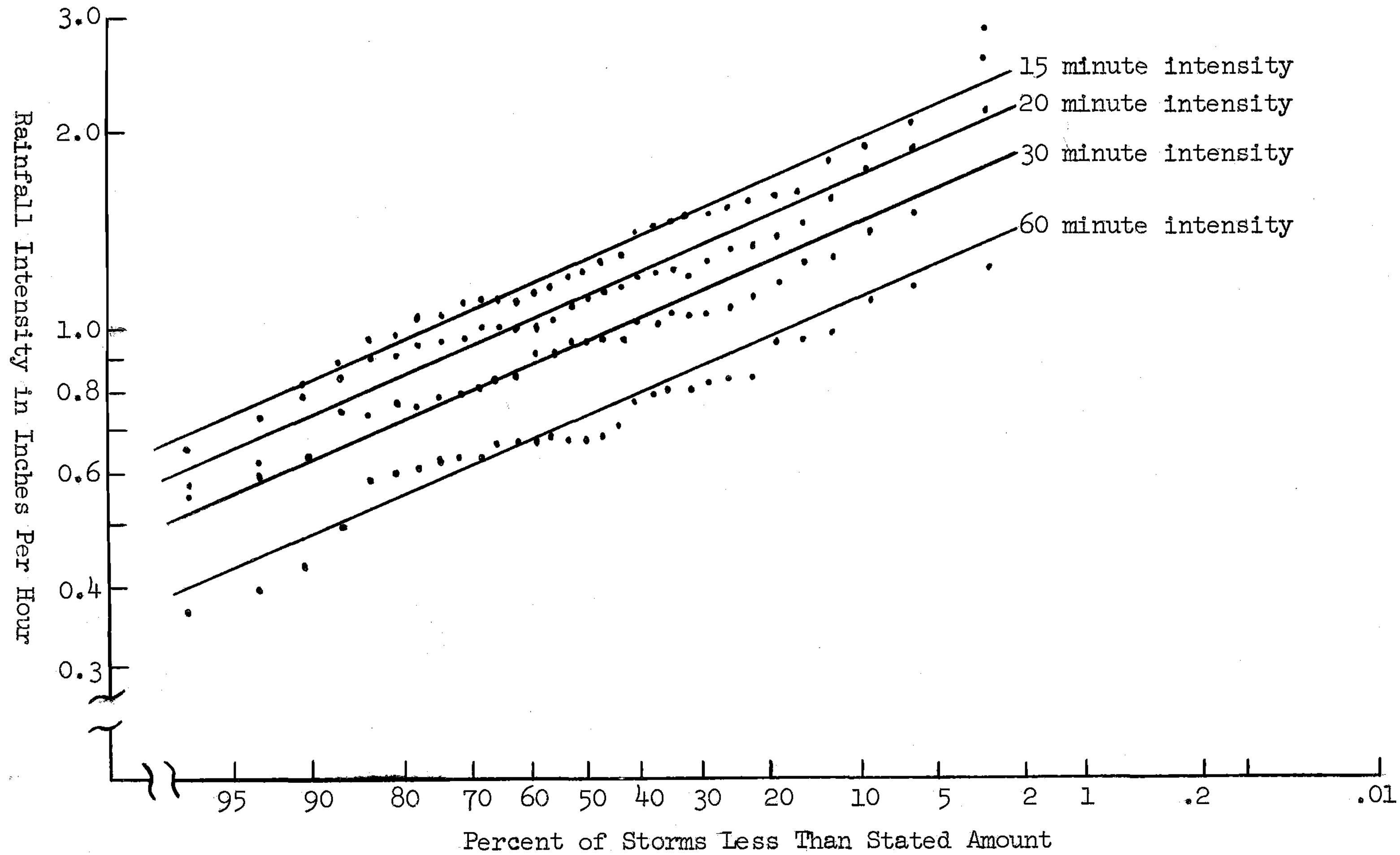

Figure B. Annual series of 15, 20, 30 and 60 minute rainfall intensity data.

APPENDIX B

DESCRIPTION OF EXISTING PROGRAMS WRITTEN FOR THE IBM 1620 DATA PROCESSING SYSTEM

DESCRIPTION OF EXISTING PROGRAMS WRITTEN FOR THE IBM 1620 DATA PROCESSING SYSTEM

1620 Correlation Program 6.0.089*

This program is designed to compute the correlation between two input variables. There are two options available; selection of isolated pairs of variables, or the choice of producing all the interrelations for a block of variables which are to be correlated to themselves or with another block of variables. Both options may be used on a given run; however, the block correlation problems must be run first. The program output consists of the number of observations, the sums, means, sums of squares, standard deviations, sums of cross-products, correlations, the square of the correlations. All calculations are in floating point form.

This program is written in SPS language.

Principal Axis Factor Analysis Using Hotelling's Iterative Procedure 6.0.091*

This program reads a parameter card giving the size of the matrix and the test criterion for testing the difference between trail vectors. The program then reads and stores the entire correlation matrix and calculates the accumulated sum of the principal diagonal of the matrix as it is stored. The first factor is then computed and punched. The sum of squares of the factor loadings is then computed and this is used in determining the percent of total variance accounted for by this factor. The percentage of total variance accounted for is calculated from a cumulative sum of squares from factor to factor. The program pauses after typing each factor to allow the operator to make a decision about extracting another factor. If extraction of another factor is desired, pushing start causes the residual matrix to be computed and a branch to extract another factor.

This program extracts any number of factors from a correlation matrix. The restrictions of this program are a maximum matrix size of 20 X 20. No residual matrices are punched; therefore, all calculations must be computed with one loading of the data.

This program is written in the FORTRAN language with FORMAT.

Varimax Factor Matrix Rotation 6.0.094*

This program uses the output from the previously described program. The maximum factor matrix that can be handled is 27 tests by 12 factors. A parameter card is read by the computer to obtain the number of factors, the number of tests, and an epsilon value for determining when a factor should not be rotated. Usually .00116 epsilon and .06993 epsilon are used. The smaller value implies that the program will not perform a rotation if the angle is less than one minute, and will cause the machine to perform more calculations. The larger value implies no rotation if the angle is less than one degree. The matrix to be used by the program can be keypunched as input in any order. The communalities are then computed, and square roots of the communalities are computed and punched and the matrix is normalized. Rotations are performed on the matrix using the varimax method; the matrix is denormalized and then printed.

This program is written in the FORTRAN language.

* Refers to the IBM library program number.

APPENDIX C

RESULTS OF STATISTICAL COMPUTATIONS

Table A. Percent variation explained by the common factors for the laboratory hydraulic conductivity variables.

Common Factor	Cumulative Percent
1	37.01
2	52.86
3	68.05
4	79.07
5	88.58
6	94.66
7	99.64
8	99.75
9	100.00

Table B. Principal components matrix of the nine hydraulic conductivity variables.

Variables	Common Factors 1	2	3	4	5
Total Porosity	.78	-.24	-.46	.17	.13
Non-capillary porosity	.45	-.53	-.49	-.23	.39
Depth	.39	-.24	.43	-.63	.19
Quartz	.40	-.48	.52	.29	-.19
Biotite	.55	-.41	.18	-.15	-.54
2 - 1 mm	.53	.13	.53	.36	.49
1 - .5 mm	.65	.59	.21	-.28	.08
.5 - .25 mm	.77	.49	-.25	-.19	-.27
< .25 mm	.78	.14	-.16	.41	-.10

Table C. Computation of Student's t values for specific gravity bottles and aluminum air pycnometer.

Item	Sample: Bottles	Air	Combination	Explanation
y	18.859	17.111		
n	51	51		
$\bar{y}$	0.37	0.34	0.03	$\bar{y}_1 - \bar{y}_2$
$(\Sigma y)^2$	355.662	292.786		
$(\Sigma y)^2)n$	6.974	5.741		
Σy^2	7.176	5.944		
ss	0.202	0.203	0.405	pooled ss
d.f.	50	50	50	pooled d.f.
s^2	0.00404	0.00404	0.0081	s^2p
$1/n$	0.0196	0.0196	0.0392	$\frac{1}{n_1} + \frac{1}{n_2}$

$$t = \frac{\bar{y}_1 - \bar{y}_2}{\sqrt{s^2p\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} = 1.910$$

Table values at 5 percent level $t = \pm (2.010)$

Hypothesis: The two population means are equal, that is $\bar{y}_1 = \bar{y}_2$

Conclusion: Since t is outside the critical regions, the population means are equal.

Table D. Simple correlation matrix for the granitic parent material variables.

Column	bd	60 cm	rt	d	q	b	15 atm.	1-2	.5-1	.25-.5	<.25	1/3 atm.
Bulk density (bd)	1.00	-.64*	.07	.10	.08	-.14	-.05	.25	-.21	-.44*	-.59*	-.17
60 cm moisture (60 cm)		1.00	-.25	.22	.10	.21	-.01	-.01	.04	.16	.16	-.23
Rock type (rt)			1.00	.16	-.53*	.34*	-.17	.11	.20	.10	.02	.06
Depth (d)				1.00	-.23	.31*	-.25	-.24	-.26	-.16	.09	.18
Quartz (q)					1.00	-.42*	-.18	.34*	.07	.01	-.23	.20
Biotite (b)						1.00	.06	-.12	.18	.28	.29*	-.11
15 atmosphere moisture (15 atm)							1.00	-.28	.16	.28	.12	-.04
1 - 2 mm (1-2)								1.00	.50*	.08	-.44*	-.26
.5 - 1 mm (.5-1)									1.00	.80*	.27	-.21
.25 - .5 mm (.25 - .5)										1.00	.70*	.13
< .25 mm (< .25)											1.00	.16
1/3 atmosphere moisture (1/3 atm)												1.00

* Indicates the variable is significant at the 90 percent level.