

SOME HYDROLOGIC CHARACTERISTICS IN
THE UTAH JUNIPER TYPE OF
NORTHERN ARIZONA

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**SOME HYDROLOGIC CHARACTERISTICS IN THE UTAH JUNIPER TYPE
OF NORTHERN ARIZONA**

By

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Frontispiece: A south-facing view of some of the experimental plots. Plots are seen as projections of green into the brown treated (cabled) area. The canyon, left-center, opens into the Verde Valley. Sedona, the portal to Oak Creek Canyon, is located by the jutting rock formation seen to the right.

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ABSTRACT

This study is part of a research effort designed to obtain basic information relating to watershed management, with particular reference to the Beaver Creek Watershed Project in Arizona. The objectives of this study were to make a preliminary determination of the disposition of precipitation falling in stands of Utah juniper (Juniperus Utahensis (Engelm.) Lemm.) growing on a fairly average range of sites on the Beaver Creek Watershed, and to explore some of the factors controlling the disposition process. Other objectives were to provide complementary information regarding soil characteristics and root distribution of Utah juniper in this area.

The study area within the Beaver Creek Watershed lies on the Mogollon Rim at an elevation of about 5,500 feet. Average annual temperature is about 55 degrees, and average annual precipitation believed to be 16 to 18 inches. Topography is rolling to hilly and occasional steep-walled canyons are cut by ephemeral streams. Parent rock is composed of heterogenous volcanics.

Nine study plots were located adjacent to three small watersheds now undergoing calibration in the Utah juniper type on the Beaver Creek Watershed. Data was collected for one year beginning in April, 1958.

The soils on all plots were identified as belonging to the Springerville series. Average soil depth for this series is predominantly between 30 and 50 inches, although variations from 6 to 94 inches were found on the study plots. These soils are very hard when dry, and very plastic and sticky when wet. An important feature of

this series is the high content of montmorillonitic clay, about 65 percent, which results in a comparatively large water-holding capacity of about $2\frac{1}{2}$ inches per foot of soil, with a pronounced swelling and shrinking accompanying the moisture changes. The consequent crack formation is believed to greatly increase the infiltration capacity of the soils.

A study of the root distribution indicates that the great bulk of roots is located within the upper 3 feet of soil. Some roots, however, are known to occur at depths of at least 15 feet. Large roots are rather uniformly distributed throughout the profile, while a concentration of fine roots occurs in the upper 18 inches of soil.

An average of 15 inches precipitation fell on the nine study plots during the year. From hydrograph records on the three adjacent watersheds, an average of about 0.20 inch occurred as surface runoff. A similar small amount was estimated to have entered the underlying basalt formation as percolation. All percolation and a disproportionately large share of surface runoff originated on only two plots, both having soils about 6 inches deep, little vegetation and slopes of about 6 percent. The balance of total precipitation, about 97 percent, evaporated from either soil or leaf surfaces. With a net reduction in soil moisture storage at the end of the year, average total evapotranspiration exceeded average total precipitation by about 3 inches.

An attempt was made to characterize the density of Utah juniper stands in relation to their influence on the disposition of precipitation. On the nine study plots, eight stand density characteristics, dealing largely with estimates of crown volume and tree number, were

measured. All stand characteristics turned out to be highly correlated with percent crown volume as measured by a spherical densiometer. Only interception was directly influenced by stand density. Of the eight characteristics, crown density as measured by the spherical densiometer proved to be best related to the amount of precipitation intercepted. This relationship, when based on individual observations, was inversely related to the square of percent crown density.

The per storm relationship between gross and net precipitation was found to be linear, and gross precipitation was found to be much more important for predicting net precipitation than stand density.

The rate of soil moisture depletion was found to be fairly constant between 65 and 5 percent of available soil moisture, and to be uniform throughout the upper 30 inches of soil. During periods of depletion, amounts of soil moisture withdrawn in either 24 or 30 inches of soil were nearly equal for all stand density classes. It was shown that total evapotranspiration of soil moisture was directly related to average soil depth and net precipitation. Average soil depth was a better predictor of total evapotranspiration of soil moisture because it reflected differences in net change in soil moisture storage and because it indirectly influenced net precipitation through its influence on stand density.

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INTRODUCTION

The burgeoning industrial, agricultural and population growth of Arizona depends upon a corresponding development of its water resource. Most of Arizona's growth has taken place in the desert valleys. The city of Phoenix, for example, has nearly doubled its population in each of the last two decades, while the number of irrigated acres has increased from about one-half million to over one million during the same period (U. S. Dept. Commerce, 1957). Since precipitation within these valleys is scant, about six to ten inches annually (U. S. Dept. Commerce, 1956), and ground-water supplies are being consumed more rapidly than they are being replenished (U. S. Dept. Interior, 1956), the increased supply of water must come from other sources.

Recognizing the problem and its urgency, the Arizona Watershed Program was started early in 1956 as a cooperative undertaking of the State Land Department, the Salt River Valley Water Users' Association, and the University of Arizona. One of the first efforts of this group was concentrated on alleviating the water supply problem to the city of Phoenix, located in the Salt River Drainage. Dr. George Barr of the University of Arizona led a group of technical consultants who examined the Salt River Drainage and its tributaries, an area of about 12,000 square miles (Barr et al., 1956), in an attempt to formulate guidelines for increasing the yield of surface water. The conclusions and recommendations of this group were published by Barr et al. (1956). Cooper (1959) using some data from this report made an economic study of multiple land use on the Salt River Watershed. The relative

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importance of the major land uses was ranked in descending order as: water, recreation, timber and grazing. One of the conclusions of the Barr group was that the most rapidly feasible method of increasing surface water supplies would involve vegetation manipulation. This conclusion was based on the knowledge that vegetation markedly affects surface runoff through its effect on evapotranspiration and soil conditions, and that the effects are logically more pronounced as annual precipitation increases.

With this report furnishing the initial impetus, a citizen's group, the Arizona Water Resource Committee, was formed to offer further guide lines for increasing surface water supplies to the Salt River Drainage. This citizen's committee is distinct from, but works in cooperation with, the Watershed Division of the State Land Department. With state and federal support, federal funds became available to the U. S. Forest Service to expand watershed management activities in Arizona.

The federal appropriation provided for two things¹: (1) a large-scale pilot project, now called the Beaver Creek Watershed Project, was to begin on the Coconino National Forest with the purpose of testing effects of intensive land management practices on surface yields of water, and (2) research, under supervision of the Rocky Mountain Forest and Range Experiment Station, to better guide the action program, and to gather basic information for watershed hydrology.

¹Aldon. 1959. Unpublished file material of the Rocky Mountain Forest and Range Experiment Station.

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The Beaver Creek Watershed is about 275,000 acres in size. Within this drainage basin are two sub-drainages, the Wet and Dry Beaver Creek Watersheds. The pilot project's action program is concentrated on about 30,000 acres of the Wet Beaver Creek Watershed, which includes three cover types: Utah juniper (Juniperus Utahensis (Engelm.) Lemm.; alligator juniper (Juniperus deppeana Steud); and ponderosa pine (Pinus ponderosa Laws.). Research of a similar kind is being conducted in all three cover types (See Figure 1).

The land management practice selected for the Utah juniper type was cabling. Arnold (1955) had shown that this practice increases grass production. In this operation the ends of a thick wire cable are attached to pins on two Caterpillar-type tractors. Moving parallel to each other about 50 to 100 feet apart, the 300 foot cable, forming an arc, is dragged along the ground. As junipers are encountered by the cable, they are uprooted and left on the ground.

To test the effect of this practice on surface yields of water, the Rocky Mountain Forest and Range Experiment Station recommended the use of calibrated watersheds. The site for three contiguous watersheds, 250, 310, and 330 acres in size, were chosen in 1956. Stilling wells, water-stage recorders and flumes were installed during 1957 (see Figure 2). A network of meteorological instruments was also established within the boundaries of the three watersheds during this period (see Figure 3). After calibration at least one of the three watersheds will be cabled in a manner similar to that now taking place over the Utah juniper type on the Beaver Creek Watershed as a part of

Figure



Figure 2. A modified Washington State College trapezoidal flume and housing for a stilling well and water-stage recorder on one of the calibrated watersheds in the Utah juniper type.

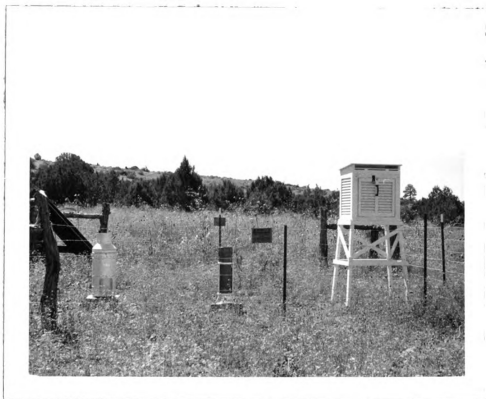


Figure 3. Weather station in Utah juniper type, showing recording and standard precipitation gages and housing for hygromograph and maximum and minimum thermometers.

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the pilot project. One of the two remaining watersheds will be held as a control to evaluate the effect of cabling on the yield of surface water.

In addition to their part in evaluating the pilot project, the meteorological network and stream-gaging devices will furnish basic information concerning precipitation, temperature, humidity and stream-flow characteristics. It was felt, however, that additional basic information was needed in relation to other factors which might affect water yields. The initiation of long-term projects in this regard could not be immediately begun since so little was known of the hydrologic characteristics of the area. Rather, a short-term project embracing many aspects of basic hydrologic research was undertaken on a plot basis to provide a portion of the initial data to be used in defining the area problems and orienting the direction of continuing research.

These short-term, basic studies constitute the subject matter of this thesis. They include measurements of evapotranspiration, interception, surface runoff and changes in soil moisture storage. These components of the hydrologic cycle were then related to stand density after a suitable method of describing Utah juniper stands was obtained. Other measurements were made of the ground surface, soil profile characteristics and root distribution of Utah juniper. Data was also taken from the meteorological network and the stream-gaging devices. It should be stressed that no attempt was made to directly evaluate the large-scale pilot project treatment program outlined earlier in this section.

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OBJECTIVES

The general objective of this study is to provide basic hydrologic data in the Utah juniper type, with particular reference to the Beaver Creek Watershed Project in Arizona. This initial data will provide a portion of the information needed to define the area problems and to orient the direction of continuing research.

Specifically, the objectives were to make a preliminary determination of the disposition of precipitation that falls in varying densities of Utah juniper stands growing within a fairly average range of sites on the Beaver Creek Watershed and to explore some of the factors which control the disposition process. Secondary objectives were to provide complementary information regarding soil properties and root characteristics of Utah juniper.

LITERATURE REVIEW

The term "watershed management" implies doing something to a watershed to achieve a certain purpose, and in this sense is an ancient practice. With the crystallization of the so-called "scientific method" it is possible to improve the efficiency of watershed management because the things done to a watershed are based upon understanding the physical principles which govern the behavior of a watershed. Physical principles governing the behavior of water have been studied in the laboratory. Heats of vaporization, kinetic motion, hydraulic flow, and a host of other properties have been studied and formulated for water. When this knowledge is carried to the field, however, it fails to provide an ability to accurately predict water behavior on a given watershed. Such a result is understandable in view of the complexity of factors operating on water. Watershed management research, then, must concern itself with devising methods of measuring the net effect of the physical complex, and synthesizing these measurements into empirical concepts which can be used to predict water behavior on a specified watershed. Knowing something of the climate, vegetation, soils, and geology of an area, we measure the amount of surface runoff, evapotranspiration, percolation and other components of the "Hydrologic cycle" and relate them to the above factors. From these relations we attempt to arrive at concepts which enable us to predict the behavior of water on any watershed.

As Kittredge (1948) points out, there are instances of watershed management research which date back many centuries. Authors sometimes

place its real beginning with a study of the effects of forest vegetation on streamflow begun by Engler in 1890 in the Emme Valley, near Wesen, Switzerland (Burger, 1929a, 1929b). Research since that time has been summarized by Zon (1927) and Coleman (1953). It is not the purpose of this review to improve on their work, but to cite those studies which are pertinent to the objectives of this study, with particular emphasis on research in the Southwest.

The Water Balance Method.

As McIlroy (1957) points out, all forms of the water balance method make use of the following basic equation:

$$P = E + O + D + \Delta W$$

P is precipitation

E is evaporation

O is surface runoff

D is subsurface drainage

ΔW is change in soil moisture

For determinations of evapotranspiration on a large scale, the catchment area balance sheet is used. A natural drainage area, ranging in size from about one to over several hundred thousand acres, is chosen. Precipitation is measured by suitably placed gages, and surface runoff measured as inflow to either natural and artificial reservoirs or by stream-gaging devices. For long time studies, ΔW can be neglected; for short time studies, it can be determined by one of the many soil sampling techniques. D is usually estimated since its direct measurement is difficult. For small areas, an impermeable substratum is desirable to eliminate this factor. E can be obtained by

subtraction. An example of the catchment area balance sheet is furnished by Kohler (1957) and by Hoover (1944). Detailed instructions for computing some of the individual components have been compiled by Johnson and Dils (1956) and by Nash (1958). Wicht and Schumann (1957) discuss standards to use in the selection of experimental catchment areas.

Where highly controlled measurements are desirable, or where men and equipment are lacking to sample large areas, lysimeters are used. These devices are essentially contained blocks of soil equipped to separately weigh the in-coming and out-going water increments. Reviews of the literature pertaining to lysimetry are provided by Kohnke, Dreibelbis and Davidson (1940) and Harrold and Dreibelbis (1955). The shortcomings may be summarized: (1) evapotranspiration is related to the size area of the surrounding crop given the same water treatment, (2) downward water movement is retarded by the air-soil interface for shallow depths, (3) soil structure is unnatural, and (4) root growth is inhibited. The alundum tension lysimeter developed by Cole (1957) is designed to provide a tension sufficient to overcome restrictions in water movement, and at the same time keep the soil undisturbed. The comparatively huge, 18x50x3-6 feet deep, Base Rock lysimeters at Sierra Ancha (U.S.D.A. 1953) rest on impermeable quartzite bedrock. Here the soil was enclosed in place.

A rather specialized and widely popular form of lysimetry involves Thornthwaite's concept of potential evapotranspiration. The following quotation is taken from Thornthwaite and Mather (1955):

"One cannot determine the amount by which precipitation fails to supply water needs for crops without knowing what these water needs are. In order to make a map showing the distribution of water deficiency (the amount by which precipitation fails to supply sufficient water) it was first necessary to make a map of water need. This most important climatic element was defined as the amount of water which will be lost from a surface completely covered with vegetation if there is sufficient water in the soil at all times for use of the vegetation. It was called potential evapotranspiration."

The method is essentially empirical, relying on mean air temperature, latitude and length of day to compute a heat index (I) roughly correlated with the amount of solar energy (Thornthwaite and Mather, 1957). Thornthwaite recognized the Oasis effect and provided buffer zones against it.

Several serious flaws appear in the Thornthwaite approach. In the first place, the relationship between mean air temperature and solar heat energy is used as a constant. As Thornthwaite himself points out (1955):

"However, since a higher proportion of the net radiation is spent on heating in arid areas, there is even with temperature a lack of conservatism which will result in some error in computing potential evapotranspiration."

Second, the relationship between mean air temperature and potential evapotranspiration is, according to Halstead and Covey (1957),

"....complicated by the fact that actual evapotranspiration tends to lower the maximum and mean temperature...."

Third, potential evapotranspiration was supposed to be a climatic parameter independent of vegetation type. Conflicting reports have emerged. Both Mather (1954) and Blaney (1952) suggest that potential evapotranspiration is related to vegetation type. Penman (1949, 1951), however, supports Thornthwaite's point of view. Kohler (1957), as a

result of findings at Lakes Hefner and Mead, proposes the use of potential evapotranspiration to mean:

".... evaporation from a free-water surface of extended proportions, but independent of any heat storage effects."

Further, he states:

"These two experiments proved rather conclusively that monthly evaporation from an existing reservoir can be reliably determined by the application of an energy budget, and that the day-to-day variations in evaporation are in accord with an empirical mass-transfer equation."

To compute actual evapotranspiration by the Thornthwaite method, a procedure is used involving measurement of precipitation, assumptions regarding surface runoff, percolation and soil moisture availability, and evaluation of soil texture and root depth (Thornthwaite and Mather 1957).

One of the most persistent problems involved in short time investigations is that of adequately determining soil moisture, particularly over large areas. A number of techniques, as outlined by McIlroy (1957), are available for this purpose, but extensive replication is needed for even comparatively small areas. One of the most common and most accurate is gravimetric sampling. The procedure is, however, time consuming, laborious, and destructive of the soil body. For continuous recording of soil moisture in place, the variation in electrical resistance with changes in soil moisture is commonly measured, using porous blocks embedded in the soil. All varieties of porous blocks have at least one major limitation. They may lack long term stability; display hysteresis effects; show dependence on temperature or salinity; measure limited ranges of soil moisture; are difficult to

embed properly in the soil. Another frequently used device is the tensiometer, which measures soil moisture directly with the use of a porous bulb filled with water and connected to a manometer. This device is subject to temperature fluctuation; measures only on the wet end of the soil moisture range (about 0.8 atmos.); requires good contact; and is subject to air leakage.

A less frequently used technique employs measurement of differences in the rate of temperature rise when heat is supplied to the soil, or else the vertical heat transfer of the soil is measured directly by heat flow plates similar to net radiometers. A description of the technique is given by Porter (Halstead, 1954). A calibration is required for each soil, since the heat transfer is dependent on the particular thermal properties of the soil. According to Baver (1956), the flow of heat will increase with increasingly dark color, increasing amounts of coarse particles and water content (specific heat), and increasing compaction and water content (conductivity). A good contact is necessary for this method as the probes and plates are rather sensitive.

The neutron scattering device is now becoming popular because it offers the advantages of rapid field measurement without additional laboratory work; it is factory calibrated; and is independent of the effects of temperature and salinity. Some of the disadvantages are high initial cost, rather elaborate safety precautions, contact problems with the liner for the test hole, and variations in volume of soil sampled with changes in moisture content. There is also some difficulty in obtaining values for small intervals (Anonymous, 1959).

Precipitation.

McDonald (1956), in a preliminary statistical analysis of selected Arizona precipitation records, found that the year to year variation in winter precipitation (November to April) exceeded the year to year variation in summer precipitation (May to October). Conversely, spatial variation was greater in summer than in winter. He points to the uncertainty of annual precipitation means in Arizona with the remark that stations with many decades of records had "95 percent confidence half-widths fully 10 percent of the mean." Secular trends, as studied with 10-year average-moving plots, were very pronounced.

Stand Description.

The importance of crown volume of trees in relation to hydrologic phenomena has generally been recognized. Early methods largely employed some version of the "crown projection" technique, a laborious procedure at best, involving hand drawings of the vertical projection of the canopy to the ground. Recent techniques have done much to improve the efficiency of this method. Spurr (1948) outlines the methods with which aerial photographs now permit rapid and wide-scale determinations of crown diameters and crown closure to obtain stand density. Two methods of rapidly obtaining an estimate of crown volume from the ground are now available. Lemmon (1956) developed the "spherical densiometer", a pocket-sized, convex, chrome mirror with a grid incised on the surface. Evans and Coombe (1959) have developed a type of pin-hole camera which reduces a photograph of a hemisphere to a flat plate.

On this photograph are imposed the track of the sun for any given day and a grid of concentric circles for each 30 degrees of altitude and radiating lines for each 30 degrees of azimuth.

Other methods have been used to measure crown volume. Cooper (1957) modified the Bitterlich technique to measure crown volumes of shrubs. Cable (1958) related surface area and weight of fascicles of ponderosa pine. When this relationship is combined with estimates of fascicle weight per tree, the total surface area of fascicles for a stand may be computed. Yamaoka (1958) related total leaf weight and breast-height diameter to obtain total transpiration for a stand of Crypomeria japonica. Canfield developed the Line Intercept method primarily for herbaceous species, but this method can be adapted to measurements of crown volume (1942).

Several authors (Bradshaw, 1943; Howell, 1941; Reveal, 1946; and Herman, 1953) have studied the characteristics of juniper stands, but only from the viewpoint of wood production. Reveal's (1946) data show that even there a poor correlation was reported between tree sizes and "maturity classes."

Interception.

To date, no information has been published concerning interception in Utah juniper. Early interception studies in other species were summarized by Horton (1919). He states that the

"amount of interception is primarily a function of storage capacity of the plant surface, the duration of precipitation, and the evaporation rate during precipitation."

Interception by trees was 0.02 to 0.07 inch per storm. The percentage of precipitation intercepted per storm is larger the smaller the storm.

Depending on species and stand density, interception values varied from 15 to 80 percent of the total yearly precipitation. Species with needle-shaped leaves intercepted relatively greater amounts of precipitation than broad-leaved species. Stemflow accounted for 1 to 5 percent of total precipitation.

Wicht and Schumann (1941) presented an historical review. They emphasized some of the limitations of the early studies, such as failure to record stemflow, failure to sample randomly, and failure to use a sufficient number of gages. These experiments were conducted on gray poplar. The results of this work confirmed the principles reported by Horton. In addition, it was suggested that condensation increases throughfall values, and that open gages on paired experiments be placed at canopy level.

Wilm and Niederhof (1941) conducted interception studies on mature lodgepole pine stands. Net rainfall increased by 0.10 inch for every foot increase in the average size of canopy openings up to about 18 feet. Net rainfall was a straight-line function of gross rainfall for all stand conditions.

Grah and Wilson (1944) demonstrated three phases of leaf-surface detention: transitory storage, or water which drops off under still air conditions; conditional storage, or water that falls off when wind disturbs the leaves; and residual storage, or water removed only by evaporation.

The work of Kittredge, Loughead and Mazurak (1948) with Canary Island pine indicated that stemflow was apparently not directly related to crown-length density, tree height, basal area, or crown area;

however, it did tend to increase as tree height relative to adjacent trees increased. Total stemflow for the plot was approximately 1 percent of total precipitation, but as much as 13 percent was recorded for an individual storm. Stemflow commenced when precipitation for a given storm reached 0.20 to 0.25 inch. Interception was greatest on the leeward side of a tree; increased with an increase in wind velocity; and decreased with increased distance from the bole.

Johnson's work (1942) with a forest of young ponderosa pine indicated that there was no significant difference in interception between seasons when amounts were adjusted to those expected for average gross precipitation.

Hamilton and Rowe (1954), working in chaparral in California, found 5 percent total net interception in buckeye-ceanothus-oak type, 8 percent in ceanothus-manzanita, and 11 percent in oak-ceanothus. The buckeye-ceanothus-oak type was partly deciduous. They state:

"Stemflow was influenced to a considerable extent by the branching habit and character of the bark of the various shrub species."

Shrubs having a smooth bark and upright stem had stemflow of nearly 11 inches out of 38 inches total precipitation. Shrubs with rough bark and a spreading branch habit yielded but 2 inches of stemflow out of 27 inches total precipitation.

Aldon and Curtis¹ studied interception according to stand density of ponderosa pine, where basal area was used as a measure of stand

¹Aldon, Earl F. and W. R. Curtis. 1958. Unpublished report of Rocky Mountain Forest and Range Experiment Station.

density. They found that between 11 and 25 percent of the summer thundershower type of storm is intercepted by pole-size stands. Pole stands of from 48 to 90 square feet basal area per acre intercepted less precipitation than stands with higher basal area. Stemflow was found to begin when 0.20 inch precipitation had fallen in a single storm. Total stemflow varied from less than 1 percent to over 8 percent of total precipitation depending upon stand density.

Evapotranspiration.

The term, evapotranspiration, is customarily defined (van der Bijl, 1957) as,

"The combined direct evaporation of water from a plant, soil or water surface and transpiration of water from plants."

Physical Principles Governing Evapotranspiration. The following account is taken from Daniels and Alberty (1956) and Haltiner and Martin (1957). Since transpiration represents but a special form of evaporation, the kinetics involved are the same. Kinetic theory postulates that molecules of any substance are in constant motion when their temperature is above absolute zero. This is the so-called Brownian motion. As the amount of heat imparted to molecules increases, so does their velocity increase. With an increase in velocity comes an increase in momentum.

Consider a body of water: at a given temperature the average velocity of the water molecules is constant. However, a distribution of velocities exists such that a certain portion of the fastest moving molecules will have a momentum large enough to overcome the attractive forces holding them in a liquid state. As these molecules escape, the

mean velocity of the remaining molecules decreases, resulting in a cooling effect. Heat is usually supplied from the surrounding medium, the mean velocity increases, and an equilibrium is established. If additional amounts of heat are supplied, as from solar radiation, the rate of escaping water molecules increases and a new equilibrium is reached.

Few molecules can escape the earth's gravitational field, so the picture is essentially one of a closed container. As the number of water molecules leaving a water surface increase, the number of collisions in the atmosphere increase. The net result is a number of water molecules having a distribution of velocities and moving in random directions. Those molecules with the lowest velocities which strike most perpendicularly to the body of water are most apt to remain. When an equilibrium is reached where the number of in-coming and out-going molecules is equal in unit time, it is known as saturation vapor pressure. As the temperature of the system increases, the saturation vapor pressure increases. The Clapeyron Equation (Daniels and Alberty, 1956) describes this relationship. Dalton showed that each kind of molecule exerts a partial vapor pressure independent of other types of molecules. The particular equilibrium obtained for water molecules, then, will be independent of other gases in the atmosphere, and dependent only on the temperature of the system. When the number of out-going water molecules exceeds the number of in-coming water molecules to a water surface, evaporation occurs. At this time the actual vapor pressure of water is less than saturation vapor pressure.

Factors Affecting Evapotranspiration. According to Halstead and Covey (1957), the available heat energy at the air-earth interface is used in one of three ways: (1) to heat the air, (2) to heat the soil and vegetation, and (3) to evaporate water. The energy used to heat air, soil, and vegetation is usually referred to as "sensible" heat, while heat energy used to evaporate water is referred to as "latent" heat of vaporization. They go on to state the apportioning of the available heat energy depends upon:

"(1) the temperature distribution in the soil and air and water vapor distribution in the air, (2) on the availability of water for transpiration and evaporation, (3) on the thermal properties of the soil, and (4) on the rate of movement and mixing of the air in and over the plant cover."

Of the four factors affecting evapotranspiration, only (2), the availability of water for transpiration and evaporation, is particularly pertinent to this study. The other factors are intimately related to methods of determining rates, rather than amounts, of evapotranspiration. They are discussed in this connection in Appendix 1.

An immediate question presents itself: how is the amount of available heat energy determined? For theoretical background the reader is referred to Johnson (1954). In summary, he shows that the heat energy available for evaporation comes from two primary sources, net radiant energy and energy supplied by the transfer of sensible heat from warm air masses. Net radiant energy is the difference between incident solar radiation plus diffuse sky radiation minus reflection of short wave radiation plus long wave back radiation. The amount of solar and diffuse radiation is fairly amenable to direct measurement, and tends to be constant when differences in day length

and cloudiness are removed. The amount of short wave reflection depends on surface properties, and is referred to as "albedo". For average surface conditions, the value 20 percent is used, but reflection may vary from over 80 percent for fresh snow to less than 10 percent for either a dense forest or water surface (Landsberg and Blanc, 1958). The amount of long wave back radiation is shown to be fairly independent of surface properties, and is primarily dependent on mean air temperature, degree of cloudiness and atmospheric humidity (Penman, 1949).

The problem of availability is almost entirely concerned with the effects that plants and soils have in modifying the flow of water to the atmosphere. The question may be asked, how does the physiology or morphology of the plant modify the material transport of water to the atmosphere? Theories of the movement of water through a plant are reviewed by Meyer and Anderson (1954), Richards and Wadleigh (1952) and Bonner (1959). The general theory is that the amount of water transported to the atmosphere in unit time is a function of the driving potential divided by the resistance. In electricity this concept is known as Ohm's law, and in plant-water relations as Van den Honert's law. It is convenient to consider this process in two stages, within the plant, and from plant to atmosphere. The driving potential within the plant is usually referred to as the diffusion pressure deficit (DPD) gradient, and is described by Meyer and Anderson (1954):

"Whenever evaporation is occurring from the walls of the cells into the intercellular spaces, the diffusion-pressure deficit of the water in the mesophyll cell walls increases. Such cell-wall diffusion-pressure deficits are primarily imbibitional in origin. Water therefore moves

into the walls from the adjacent protoplasm, resulting in turn in a movement of water from the vacuole into the protoplasmic layer. The resulting increase in the diffusion-pressure deficit is in turn propagated to all parts of the cell. Within the lamina of the leaf, gradients of diffusion-pressure deficits, gradually increasing in magnitude from cell to cell in the direction in which water is moving, are established between the xylem ducts and the cells from which evaporation is occurring. Water therefore moves from a given vessel or tracheid into adjacent cells, which results in the development of a tension in the water column occupying that element of the xylem. Concurrently tensions are similarly developed in other xylem ducts within the leaf. The diffusion-pressure deficit of the water in the xylem elements will be increased by the amount of this tension. Water under a tension (negative pressure) of 13 atm., for example, has a diffusion pressure just 13 atm. less than that of pure water at the same temperature which is not under tension."

It is seen that the DPD gradient within the plant is expressed in terms of Dixon's "cohesion of water" theory, where tension, or "negative pressure" applied to a contained water column is transmitted equally to all parts of the column because of the cohesive attraction of the water molecules therein. It is further shown that the DPD in the leaf mesophyll cells seldom exceeds 50 atmospheres, so that the total gradient from soil to mesophyll cell cannot exceed this amount. Resistance to viscous flow within the plant is comparatively small, so that there is no real problem of water availability within the plant. Bonner then shows that resistance to diffusion within the plant tissue is uniform, so that the final expression for diffusion within the plant follows Fick's second law.

The chief barrier to transpiration occurs from leaf to atmosphere. Milthorpe and Spencer (1957) have conveniently expressed this problem by the following formulas:

$$T = \frac{D(e_1 - e_a)}{R}, \text{ where } T \text{ is the amount of water transpired, } D \text{ is the}$$

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co-efficient of diffusion, e_l and e_a are the partial pressures of water vapor between the leaf and ambient air, and R is the resistance.

$$R = d + \frac{1}{S_c + S_D / [1 + S_D (1/S_I + 1/S_W)]}, \text{ where } d \text{ represents the external resistance encountered by the bulk diffusion of vapor away from}$$

the leaf and S_c , S_D , S_I , and S_W the conductances (reciprocals of resistance) of the cuticle, stomata, substomatal cavities, and cell wall which constitute the various parts of the paths of flow of vapor from liquid surface to the surrounding air. Since the DPD gradient from leaf to air may easily exceed 1,000 atmospheres, it is evident that the resistance may be nearly a million times that encountered within the plant. Conductances of the substomatal cavities and cell wall are so large that they will have little comparative effect on the amount of water transpired. The effect of cuticle is imperfectly understood, but, since less than 10 percent of total transpiration usually occurs through this layer, its importance is minimized. Conductance of the stomata therefore assumes major importance in considering the availability of water for transpiration. This subject is treated in detail by Meyer and Anderson (1954) and need not be reiterated here. The work of Milthorpe and Spencer (1957) casts additional light on the regulatory function of the stomates:

"Stomatal movement was found to exert a large controlling influence on the transpiration rate, whereas water content has an extremely small or negligible effect. An approximately inverse linear relation between transpiration rate and logarithm of resistance to viscous flow through the leaf is believed to be the resultant of an inverse curvilinear relationship between the diffusive conductance of the stomata and log. leaf resistance and the decreasing difference of vapour pressure arising from the

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higher transpiration rates with increasing stomatal conductances. Nevertheless, the relation demonstrates that the transpiration rate is influenced by the degree of stomatal opening throughout its entire range."

A serious problem inherent in most methods used to determine evapotranspiration concerns the availability of soil moisture. Is water equally available to plants from field capacity to wilting point? If not, then how can this relationship be described? This question was brought to a head in a report by Veihmeyer and Hendrickson (1955), which invited discussion from other authorities in the field. Unfortunately, no general agreement was reached; however, certain foci of disagreement emerged. They pertained to: the suitability of various techniques for determining water loss; the measurement of small changes in soil moisture near the wilting point; the influence of different soil types on the amount of water held at various tensions; the effect of soil diffusion pressure deficit (DPD) as related to DPD at the leaf-air interface. Smith (1959) attempted to answer the question: "which method of potential evapotranspiration estimation, combined with which theory of the variation of actual evapotranspiration with soil moisture, gives results which are closest obtained by observation?" The relationship between potential and actual evapotranspiration varies with assumptions made in regard to the influence of available soil moisture on the rate of transpiration. Thornthwaite's method uses the assumption that the above relationship varies linearly with the amount of available water in the rooting zone of the crop. Veihmeyer's assumption is that, between field capacity and wilting point, soil moisture has virtually no effect on the rate of transpiration. Penman's

method uses an assumption intermediate between Veihmeyer's and Thornthwaite's. Smith concludes:

"It has been demonstrated that the moisture status of the soil cannot be estimated on the basis of using figures of potential evapotranspiration alone. It is necessary to account for the fact that actual evapotranspiration is not always equal to potential evapotranspiration. The theory that most closely fits the observed facts is that of Thornthwaite."

Richards and Wadleigh (1952) have intensively reviewed the literature on soil moisture availability, and no attempt will be made to improve on their work. Perhaps the most significant development since then concerns the work of Philip (1958). Reviewing Walters and Wadleigh's work, Philip (1958) states that Wadleigh had contended that the presence of solutes in the soil water contributed to the DPD against which the plant had to work; while Walter held that the presence of solutes was of no importance. Philip (1958) showed that both were right depending on the circumstances. Under conditions of high soil moisture stress and even moderate transpiration, much of the final transfer of water from soil to root takes place as vapor across a narrow gap surrounding the root. The narrow vapor gap acts as a semi-permeable membrane eliminating the solutes as a factor in the soil-to-root DPD gradient. Under conditions of low soil moisture stress and low rate of transpiration, transfer takes place as liquid water, and solutes do contribute to the soil-to-root DPD gradient.

Methods of Determining Evapotranspiration. The review of methods available for determining evapotranspiration follows the outline of McIlroy (1957), with explanations and evaluations taken from original papers whenever possible. The methods available fall into four groups

and are based respectively on determining:

- a. The water balance of the evaporating system.
- b. The upward flow of water vapor in the air layers near the ground.
- c. The energy available for the conversion of liquid water into vapor.
- d. A combination of (b) and (c).

The water balance method has been reviewed previously. Methods (b), (c), and (d) pertain more directly to determining rates of evapotranspiration, rather than amounts over a longer period of time. For this reason they are given a detailed treatment in Appendix 1.

Evapotranspiration Studies Pertaining to Southwestern Species.

Roeser (1949), using a simple type of lysimeter in Colorado greenhouse experiments, compared use of various species of tree seedling. Tree seedlings ranked according to increasing water use were: limber pine, ponderosa pine, Douglas fir, and Engelmann spruce.

McGinnies and Arnold (1939), employing the same technique with grasses in Arizona, found that water use of perennial grasses was relatively uniform. He also found that trees and shrubs were not as efficient users of water as perennial or annual grasses.

Price (1958) cites the work of Rich (1952):

"At the Sierra Ancha Experimental Forest in central Arizona from 1936-1939 water use of several plants was determined from lysimeters. Perennial grasses grown in lysimeters under natural rainfall at an elevation of 2,500 feet used 92 percent of the precipitation, winter annuals used 98 percent, and 89 percent of the precipitation was lost from bare soil by evaporation. At an elevation of 5,100 feet comparative water use was 81 percent of the precipitation for grasses, 84 percent for evergreen shrubs, and 78 percent loss from bare soil.

"Watersheds in the mixed grassland-chaparral zone (elevation 3,800 feet) in central Arizona have evapotranspiration losses ranging from 94 percent to 98 percent of precipitation; grassland-chaparral watersheds (4,500 - 4,900 feet), from 90 percent to 95 percent; forested watersheds (elevation 5,500 - 7,800 feet), from 77 percent to 90 percent, depending on depth of soil and slope.

"Consumptive use during the summer period was about the same as precipitation and was related to moisture available. Little or no water other than surface runoff was yielded to streamflow during the summer. Water use during the winter depended on growing conditions. Surplus water first satisfied the soil-moisture deficit and the balance was yielded as streamflow. Type of vegetation cover and its consumptive use in the spring growing season is believed to affect the amount of water yielded."

Commenting on the San Dimas lysimeters in California, Price (1958) states:

"Sierra Ancha studies have been verified from results of the San Dimas lysimeters in California (Colman and Hamilton), 1947. Woody species utilized all available moisture during the long, dry summer characteristic of that climate. Grass did not use appreciable moisture below 3 or 4 feet. During the winter season, pine and grass utilized the water more rapidly than scrub oak. In the years before the lysimeters were planted to woody species, they were sown to annual grass, which gradually changed to a grass-forb cover. While the soil-water loss under the annual grass did not extend below 4 feet of soil, the water in the lower soil layers was depleted when the stand of summer-growing forbs appeared (Colman), 1953."

Blaney, Taylor and Young (1930) measured evapotranspiration in the chaparral type in California. They found that

"A seasonal rainfall of less than nineteen inches is usually consumed by the brush cover before a portion of it reaches the ground water."

and that grasses and weeds consumed only 10 to 12 inches of precipitation.

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Dortignac (1956) studied relative water use of pinyon pine and Bouteloua gracilis grass in the Manzano Mountains of central New Mexico at an elevation of about 7,500 feet. Soil moisture was determined by electrical resistance blocks. When winter precipitation was sufficient to extend to limestone bedrock at 30 inches, evapotranspiration by pinyon pine exceeded that of blue grama.

Evapotranspiration Related to Stand Density.

Studies relating evapotranspiration to stand density are comparatively few in number. Usually, stands of different species are compared. Goodell (1952), reporting on the effects of thinning lodgepole pine stands at Fraser, Colorado, states:

"The evaporation and transpiration losses of moisture from the soil were found to be unaffected by the thinning treatments. This result is in support of the conclusion reached in the earlier study of harvest cuttings in mature lodgepole pine (Goodell and Dunford, 1948). In that study it was apparent that the effects of the cutting on autumn soil moisture were produced not by decreasing the soil-moisture losses but rather by increasing the rainfall reaching the soil. In the present study, the net rainfall was unaffected by the treatments and no influence was found on the soil moisture of late summer."

Douglass¹, in a study of thinning loblolly pine in South Carolina, found daily evapotranspiration rates to vary with basal area per acre. Daily evapotranspiration from April to September was 0.172, 0.146, and 0.133 inches for stands having 150, 75, and 45 square feet basal area per acre respectively.

¹Douglass, J. 1958. Unpublished report. Southeastern Forest Experiment Station.

Lull and Axley (1958) found total evapotranspiration from stands of pine poles, pine saplings and reproduction to be nearly the same in five feet of soil from April to November.

Moyle and Zahner (1954) studied soil moisture depletion by a young, even-aged hardwood stand and an all-aged cull stand of hardwoods in southeastern Arkansas. No differences in soil moisture use were measured.

Root Characterization.

According to Furr and Reeve (1945),

"While the distribution of roots varies greatly with species and soil, the concentration of absorbing roots is typically greatest in the upper part of the root zone and near the base of the plant, and decreases with soil depth or distance from the plant."

Stephenson (1935) discusses the distribution of roots of orchard trees growing on fine clays. He notes that root penetration is accomplished mainly through worm holes, insect burrows, cracks and old root channels, and that most of the roots are confined to the surface where soils are more permeable and better aerated. Where open spaces are found, such as cleavage surfaces of rock or soil, the roots will proliferate extensively.

Kramer (1946) found that suberized roots were able to absorb water, and pointed out that when soils were too dry for root elongation this process might be of major importance for plant survival. Breazeale and Crider (1934) have shown that

"A plant which has a tap root growing down into a moist subsoil, with its lateral roots in a surface soil which has been reduced to wilting point, is able to draw a certain amount of the water from the subsoil and exude this water

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into the surface soil and keep the soil which is in direct contact with the feeding roots at near the wilting percentage. This phenomenon may enable a plant to tide over periods of moisture stress."

Working with palo verde and mesquite in Arizona, they show that this process may be reversed, enabling roots to elongate in soils apparently at wilting point.

According to Johnsen¹, junipers have both lateral and tap root development. Young juniper have a pronounced tap root development; the lateral system becoming prominent with age. Laterals originate from tap roots at a depth of several inches below the soil, move downward and then outward to distances of over 100 feet in mature trees. Feeder roots concentrate under tree crowns and at the end of the laterals. Laterals are deepest in coarse soils, however, in rocky soils they may penetrate the crevices to unknown depths. Johnsen has photographed juniper roots 14 feet down a rock crevice.

¹ Johnsen, T. 1958. Personal communication.

DESCRIPTION OF THE STUDY AREA

Location.

The Beaver Creek Watershed is a tributary of the Verde River Watershed, which in turn is a tributary of the Salt River Watershed (See Figure 4). The study area is located within the Beaver Creek Watershed in the northeastern corner of Yavapai County, Sec. 1, R6E, T15N and Sec. 31, R7E, T16N, in north central Arizona along the Mogollon Rim. It is approximately 60 miles south of Flagstaff¹ and 30 miles southeast of Sedona (See Figures 5 and 6).

Climate.

Long-term weather records are not available for the study area. U.S. Weather Bureau records (U.S. Dept. of Commerce, 1958) of precipitation are shown for stations at Ash Fork, Payson Ranger Station and Cibecue in Table 1. These stations are located to the northwest, south and southeast of the study area along the Mogollon Rim by distances of 50, 35, and 95 miles respectively. They were chosen because they straddle the study area, had comparatively long-term records, and were similar to the study area with respect to cover type, elevation and annual temperature (See Table 1).

Precipitation probably averages between 16 and 20 inches per year on the study area. Records of precipitation taken from the network of

¹ Location of the Research Center from which this study was conducted.



Figure 4. State of Arizona -- relation of Beaver Creek Watershed to Salt River. Dark bar in east-west position is the Salt River; light bar in north-west position is Verde River; Beaver Creek Watershed is shown as irregularly darkened area leading into light bar just after it slants to the northwest.

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Figure 5. Location map of study area.

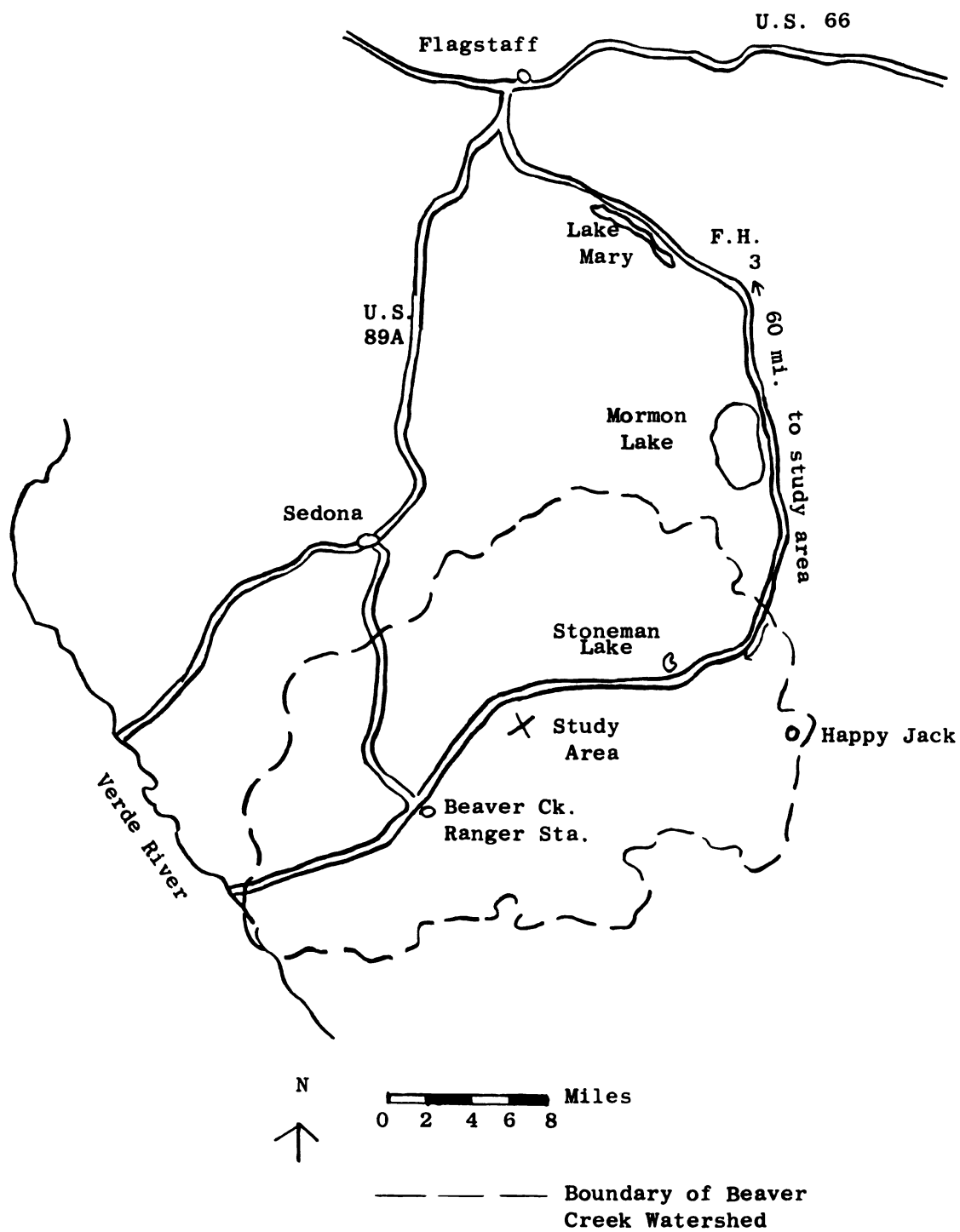




Figure 6. The study area.

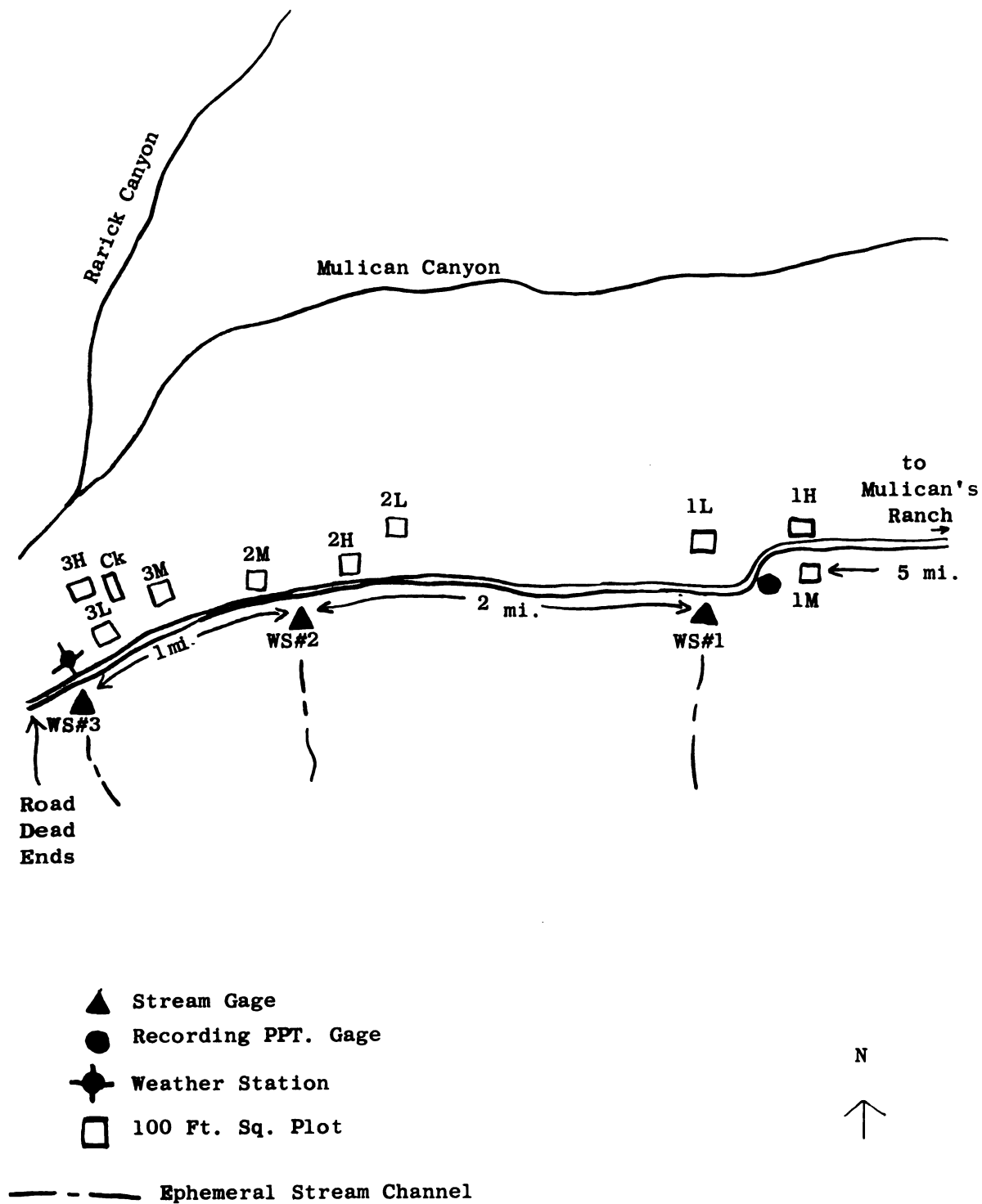


Table 1. Records for Ash Fork, Payson Ranger Station, Cibecue - Average Precipitation

Month	Ash Fork (inches)	Cibecue (inches)	Payson Ranger Station (inches)
January	1.00	1.51	2.03
February	1.19	1.72	2.21
March	1.05	1.80	1.79
April	0.94	0.99	1.12
May	0.31	0.44	0.36
June	0.45	0.58	0.59
July	1.75	2.42	2.37
August	2.48	3.24	3.57
September	1.47	1.92	1.98
October	0.69	1.24	1.04
November	0.60	1.37	1.45
December	1.27	1.69	2.00
Annual	13.20	18.92	20.51

<u>Station</u>	<u>Years Record</u>	<u>Elevation (ft.)</u>	<u>Annual Temperature (°F)</u>	<u>Cover Type</u>
Ash Fork	43	5140	54	Pinyon-juniper
Cibecue	24	5300	54	Pinyon-juniper
Payson R.S.	50	4850	53	Pinyon-juniper



gages on Beaver Creek in the Utah juniper type show 27, 19 and 13 inches for 1957, 1958, and 1959 to October 31 respectively. The precipitation occurs as short-duration, high intensity summer storms (See Figure 7) originating over the Gulf of Mexico, and as one to three day winter storms of low intensity originating over the Pacific¹. Maximum 10-minute intensities for storms larger than 0.30 inches averaged 2.21 and 0.44 inches per hour for summer and winter periods respectively during the period of study.

The distribution of the storms is worthy of comment. Periods of 75, 42 and 41 consecutive days with virtually no precipitation occurred. On the other hand, about 45 percent of total precipitation for the study period occurred in a 31-day period from September 7 to October 6. One storm during this period accounted for about 25 percent of total precipitation.

Local ranchers report that snow is infrequent and of short duration on the ground. Two years of personal observation support this view. The author also observed that soil freezing is sporadic during the winter, never penetrating deeply or lasting for more than a day or two.

¹Curtis. Unpublished Report. 1958. Files of the Rocky Mountain Forest and Range Experiment Station.

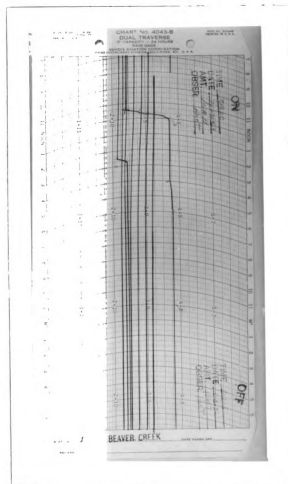


Figure 7. Record taken from recording precipitation gage near the study plots. An intense summer storm.

Average monthly temperatures shown below are taken from the hygro-thermographs records at the Utah juniper weather station:

Year	Month												
_____	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Ann.</u>
1957				*	58	72	76	72	69	56	42	42	
1958	40	44	42	50	66	74	78	76	68	56	45	45	
1959	40	39	46	57									
Ave.	40	42	44	54	62	73	77	74	68	56	44	44	56

*Instrument installed.

The maximum and minimum recorded temperatures were 104 degrees and 6 degrees recorded in June, 1958, and November, 1958, and February, 1959, respectively. Relative humidities of 5 to 15 percent are not uncommon during the usually dry spring and fall.

Vegetation.

Utah juniper occurs as the primary overstory species on some nine million acres of land in Arizona¹. On the Beaver Creek Watershed it occupies an elevation zone roughly between 4,500 and 6,000 feet. Above it lies the alligator juniper type, and below it the semi-desert grass-land type. It is found primarily in association with pinyon pine (Pinus edulis Engelm.) at the higher elevations, and with chaparral species, primarily turbinella oak (Quercus turbinella Greene), at the lower elevations. On the small, calibrated watersheds adjacent to the study plots, Utah juniper occurs as nearly a pure type.

¹Jameson. Unpublished file material of the Rocky Mountain Forest and Range Experiment Station.

Geology and Physiography.

The 1928 Geologic Map of the State of Arizona shows the entire Beaver Creek Watershed as an area of heterogenous Tertiary and Cretaceous volcanics. Detailed geologic maps are not available, but Figures 8 and 9 show the heterogenous character of the volcanics within 4 miles of the study area. The underlying rock formations range from red, porous cinders to bluish, dense basalt. Soil pits on the study area invariably "bottom out" on a basalt layer.

A topography map of the Camp Verde Quadrangle published by the U.S. Geological Survey in 1936 shows the land surrounding the study area to be rolling to hilly with steep-walled canyons cut extensively across the Mogollon Rim. The study area is located on a broad, rolling ridge top between these deeper canyons. (See Frontispiece) at an elevation of about 5,500 feet. All streams along the Mogollon Rim within the general area of the study plots are ephemeral.

Soils.

A soil-vegetation reconnaissance survey of the Beaver Creek Watershed was initiated in 1958. The Utah juniper type was mapped in 1959. Generally, the soils may be described as fairly shallow, 12 to 48 inches deep, with large local variations in depth. Rock, of pebble to boulder size, is common in the surface foot of soil. The top inch is silty clay loam, grading into clay below. Montmorillonitic type clay predominates, as evidenced by pronounced swelling and cracking with changes in soil moisture. The soils on the study plots were tentatively identified as belonging to the Springerville series.¹

¹Milo James, State Soil Scientist, Soil Conservation Service

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Figure 8. View taken at a cinder pit within 4 miles of the study area. Soils of the Springerville series are underlain by an irregular layer of dense, bluish basalt which is underlain by compacted, buff-colored cinders. Rocks point up the difficulty of sampling for moisture or depth.



Figure 9. View taken within 100 yards of Figure 8. Underlying rock formation is composed of porous, reddish brown cinders.

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Land Use and History.

The general area of the study plots remained "open" land until the establishment of the Coconino National Forest in the early 1900's. Since access roads are few and far between, the primary land use was winter range for cattle. As the Verde Valley became more settled, a small demand was made upon the area for fence posts and fuelwood. With the gradual opening up of the area for the Beaver Creek Watershed Project, an abrupt increase in the number of deer hunters occurred. The area is now part of an allotment for winter cattle range.

Description of Plots

Location. The plots are located between the weather station at Watershed #3 and the recording gage on Watershed #1, a distance of approximately 3 miles (See Figure 5). Plots are located just off the small watersheds, but within 1/8 mile of the road connecting the flumes of Watersheds #1, #2 and #3.

Number and Size of Plots. Nine main plots 100 feet square and one¹ 25 x 100 foot check plot were established. The nine main plots were divided into a grid with 100 equidistant intersections. Numbered stakes were driven into the ground at each intersection, making 10 rows of 10 stakes and forming a 10 x 10 foot grid. A similar procedure was used for the check plot. All Utah juniper was cut on and

¹Because of the limitations of time and man-power, it was impossible to clear three areas for check plots as originally planned. It was felt that a smaller check plot was adequate since the variability of most factors was appreciably decreased by removing the trees and shrubs.

within 100 feet of the check plot boundaries to eliminate live roots, and the plot was then cleared of slash.

Stand Composition and Density. Species of trees or shrubs other than Utah juniper did not exceed 10 percent of the crown density or number of individuals growing on each plot. These were usually turbinella oak or pinyon pine.

The nine main plots included three plots each of three stand density classes as measured by a spherical densiometer (See Stand Description for an explanation of the spherical densiometer). They were: 10 to 25 percent, 35 to 45 percent and 55 to 65 percent (See Figures 10, 11 and 12). Exploratory work with the spherical densiometer indicated 65 percent maximum crown density in the study area. A crown density of 10 percent is about the minimum that occurs uniformly over an area of 100 feet square. In selecting plots for this study, the densest and sparsest, naturally occurring, typical stands of plot size were chosen and inventoried first. The intermediate density class was then established with density about midway between the densest and sparsest.

Surface Cover. Unusual surface cover conditions were avoided, such as concentrations of herbaceous vegetation, surface rock or slash from fence post cutting. Jeep roads, well-used cattle trails or former camp sites were excluded. Surface cover was inventoried by stretching a tape along the rows of stakes on each plot and recording observations at whole foot intervals. One thousand observations were thus taken on each of the nine main plots. When juniper leaf litter was encountered, its depth was measured to the nearest $\frac{1}{4}$ inch. Results are shown in Table 2. Note the fairly regular increase in percent litter and



Figure 10. A light density plot (9.9 percent).



Figure 11. A medium density plot (39.8 percent). Note precipitation gage in left foreground.

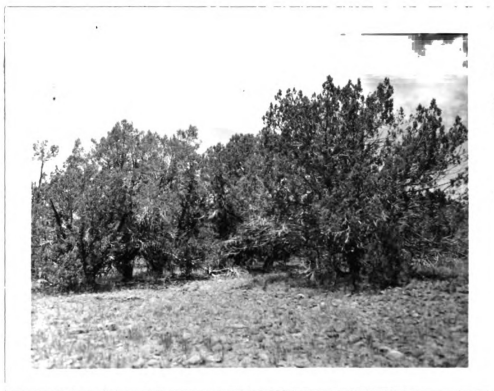


Figure 12. A heavy density plot (58.6 percent).



Table 2. Surface cover survey.

Plot	Rock	Bare Ground	Litter	Misc. ¹	Average Litter Depth	
					Where Sampled	Over Plot
	percent of area				inch	
1L	39.4	53.0	2.0	5.6	0.38	0.008
2L	38.2	54.0	2.9	4.9	0.74	0.021
3L	43.6	42.2	11.9	2.3	0.79	0.094
Ave.	40.4	49.7	5.6	4.3		0.041
1M	47.1	42.8	8.7	1.4	0.66	0.057
2M	36.5	45.1	16.4	2.0	0.82	0.134
3M	26.9	58.6	12.0	2.5	0.64	0.076
Ave.	36.8	48.8	12.4	2.0		0.089
1H	41.0	35.0	18.6	5.4	0.97	0.180
2H	36.9	46.3	16.6	0.2	0.75	0.124
3H	24.3	46.4	26.7	2.6	0.64	0.171
Ave.	34.1	42.6	20.6	2.7		0.158

¹ Includes soil cracks, herbaceous vegetation and large branches or fallen tree trunks.

average litter depth over the plot with an increase in stand density. Juniper litter does not occur over the entire plot, of course, but was expressed on a plot basis to permit comparison.

Soils and Slope. Between and within plots, soils were as uniform as possible with regard to rock content and soil type. Soils are discussed in detail in a separate section.

It was felt desirable to locate the plots on well-drained slopes not to exceed 10 percent. Levels were run on each plot with a transit and rod. Percent slope is shown below:

<u>Plot</u>	<u>Percent Slope</u>	<u>Plot</u>	<u>Percent Slope</u>
1L	4.8	3M	3.1
2L	5.7	1H	5.8
3L	3.1	2H	5.4
1M	6.6	3H	2.6
2M	4.5	Ck.	2.3

EXPERIMENTAL PROCEDURES AND RESULTS

General.

The disposition of precipitation was determined according to the "water balance" method which uses the formula:

$$\text{Ppt.} = \text{SRO} + \text{DS} + \text{SF} + \text{P} + \text{I} + \text{Et(s)} + \Delta \text{SM, where}$$

Ppt. - precipitation
SRO - surface runoff
DS - depression storage
SF - subsurface flow
P - percolation to groundwater
I - interception
ET(s) - evapotranspiration from the soil
 Δ SM - change in soil moisture

Surface runoff, depression storage, subsurface flow and percolation constitute minor components in the disposition process, and are discussed together. Precipitation and interception likewise form an individual study. Change in soil moisture and evapotranspiration from the soil are treated together.

Methods used to describe stand density are discussed in a separate section, as are the characterization of Utah juniper root distribution and soil properties.

Stand Description.

The presence of vegetation on a given area influences either directly or indirectly all of the variables in the "water balance" equation. The greater the mass of vegetation, the greater the expected influence. The problem lies in finding some easily measurable vegetative characteristic as an index of this influence. The vegetative

characteristic most likely to influence the disposition of precipitation in juniper stands is total crown volume per unit area, rather than the more conventional measures of usable wood volume or components thereof. Both volume and surface area of material in the crown are good indexes of leaf litter and organic matter contributed to the soil. Leaf litter and organic matter in turn influence infiltration and surface runoff. In addition, the volume or surface area of leaf material is presumably a good index of the amount of rain or snow intercepted and the amount of water transpired by the plant. Crown volume likewise influences micrometeorology, which in turn influences the amount of water evaporated. Some direct measure of the total crown volume or leaf surface per unit area therefore seems the best way of describing stands for this study. Actual weighing of leaf material, or making volume or surface area determinations are extremely time consuming methods, and would destroy vegetation on the plots.

Cooper's development of the Bitterlich method (1957) is unsatisfactory because of the wide-spreading crowns which restrict the visibility of the observer in the denser stands. Canfield's Line Intercept method (1942) offers promise since it is a standardized technique which can be applied to Utah juniper, and it permits fairly rapid field work. A simple count of number of individuals per unit area by height classes is likewise a standardized technique and permits very rapid field and office procedures. Number of individuals per unit area multiplied by average crown length, although not a recognized technique, would permit rapid field work and would also reflect differences in age, size and crowding effects among the various stands of plot size.

Lemmon (1956) recently developed a pocket-sized spherical densiometer for "determining from a point the relative amount of light that is cut off by specific areas of the forest overstory." A convex mirror of highly polished chrome is fitted in a recessed box 3 1/2 x 3 1/2 x 1/8 inch. A cross-shaped grid containing twenty-four 1/4 x 1/4 inch squares is incised on the mirror surface. The observer visualizes four equidistant dots in each square, and records the number which occur in the reflection of the overstory. Each dot represents nearly 1 percent. Four measurements are taken at each selected spot, one measurement facing each cardinal direction. Crown density is computed according to the following formula:

$$\% \text{ crown density} = 100\% - \frac{(\text{Tot. No. Dots Not Occupied}) \times 100\%}{(100 \text{ Loc.} \times 4 \text{ Readings} \times 96 \text{ Dots/Reading})}$$

The height at which the densiometer is held depends upon the purpose of the observation. In field trials, using different operators and different instruments, there was no significant difference among measurements of overstory density. The spherical densiometer appears to offer good promise of characterizing stands of Utah juniper on plots as they influence the disposition of precipitation.

To test the suitability of these various techniques, the density of the plot-size stands of Utah juniper was determined by the following methods and the results compared with each other:

1. Percent crown density using a spherical densiometer (%CD-D).
2. Percent crown density using the Line Intercept method (%CD-L).
3. Number of trees per plot higher than 3, 6 and 10 feet.
4. Total length of live crown per plot on trees higher than 3, 6 and 10 feet.

Stand density measures were tested against differences in interception and soil moisture change, which, outside of evapotranspiration from the soil, were the major components in the disposition process. When differences in precipitation are held constant, differences in evapotranspiration from the soil are largely a function of interception and soil moisture change, so that a stand density measure related to interception or change in soil moisture would also be related to evapotranspiration from the soil. Results of these analyses are discussed in the appropriate sections. The best stand density measure would be the one best able to predict the amount of precipitation intercepted or the amount of soil moisture used. If more than one stand density measure had nearly equal predictive value, preference would be given to the most efficient one for field and office work.

Spherical Densiometer Measurements. A spherical densiometer was used to measure crown density at each of 100 points on the 10 x 10 foot grid on each plot. The instrument was held at a height of 10 inches above the ground, the height of the precipitation gage used in the interception study. Four readings per location were taken, one facing in each cardinal direction.

Line Intercept Method: Lines were run down the ten rows of stakes established on each plot. Live crown projection over the tape was recorded to the nearest foot. A 12-foot pole was used to determine a vertical line from the crown to the tape. Holes or irregular crown edges were measured if they exceeded one foot in length along the tape.

Plot Tally Method. A tally on each of the nine main plots was made of the number of individuals by height class and the length of live crown of each individual.

Results.

The characteristics used to describe the density of plot-size stands of Utah juniper are summarized in Table 3. Correlation coefficients of percent crown density by the densiometer (%CD-D) with all other measures are shown at the bottom of the table. The strong correlation makes use of two or more measures unlikely in any multiple regression with interception or soil moisture. It is worth noting that correlation coefficients improve with increase in tree height and increase in tree height associated with length of live crown.

Utah Juniper Root Distribution.

Utah juniper, like any other plant, will use soil moisture from soil zones influenced by its roots. Proper understanding of the transpirational use of water therefore requires knowledge of the extent to which roots are distributed throughout the soil profile. Of primary importance to watershed management is a knowledge of the root-depth distribution of the various plant components on the watershed. Assuming a non-restrictive soil depth, a deep-rooted species will transpire more water than a shallow-rooted species. The amount of water transpired will affect the amount of water remaining for surface runoff or percolation.

Two methods were used to determine depth distribution of Utah juniper roots. In the first, soil profiles along the recently

Table 3. Summary of stand description inventory data.

Plot. No.	No. Trees Per Plot Higher Than			Total Live Crown Length Per Plot of Trees Higher Than			Crown Cover Using	
	3 ft. ft.	6 ft. ft.	10 ft. ft.	3 ft. ft.	6 ft. ft.	10 ft. ft.	Densiometer percent	Line Intercept percent
1L	32	9	3	173	86	41	16.2	13.8
2L	15	9	3	104	81	35	9.9	8.3
3L	25	16	10	232	194	151	23.7	21.3
Ave.	24.0	11.3	5.3	169.7	120.3	75.7	16.6	14.5
1M	38	36	23	404	398	298	46.5	41.3
2M	59	50	33	587	550	420	39.9	37.8
3M	41	33	23	420	388	314	39.8	33.9
Ave.	46.0	39.7	26.3	470.3	445.3	344.0	42.1	37.7
1H	48	36	26	500	451	374	58.6	58.5
2H	72	55	37	783	705	574	60.7	62.1
3H	88	72	43	854	785	574	56.9	56.3
Ave.	69.3	54.3	35.3	712.3	647.0	507.3	58.7	59.0
Corr. Coef.	.85	.86	.90	.89	.90	.93		.81

constructed Black Canyon Highway were freshly exposed and root counts made by size and depth distribution. The area of investigation lies about three miles west of the study plots. The vegetation is similar to them and the soils belong to the Springerville series.

In the second method, five randomly selected soil moisture samples were saved from each six-inch depth interval on each of the nine study plots. The five samples were combined, reduced to a slurry by adding water, and washed through a 2 mm screen. Only a very few of the finest rootlets passed through the screen; the majority were retained. Separation of rocks and roots was accomplished by air drying the roots, submerging both in water, and screening off the roots as they floated to the surface. This process achieved almost 100 percent root recovery. The roots were then oven-dried and weighed.

Results. The distribution of roots with depth using the soil profiles was computed and the average number of roots per square foot is plotted against depth in Figure 13. From the second method, percent oven-dry root weight $\times 1,000$ /oven-dry weight of soil is also plotted against depth in Figure 13. These values are averages for plots with an average soil depth of at least 36 inches.

It is apparent that the great bulk of roots is concentrated in the upper 36 inches of soil (See Figures 8 and 14), and that a concentration of fine roots occurs in the upper 18 inches of the soil profile. Larger roots appear to be quite generally distributed within the upper 36 inches. The concentration of roots so near the surface can probably best be explained in relation to the frequency of soil moisture recharge. There is no water table to encourage deep root

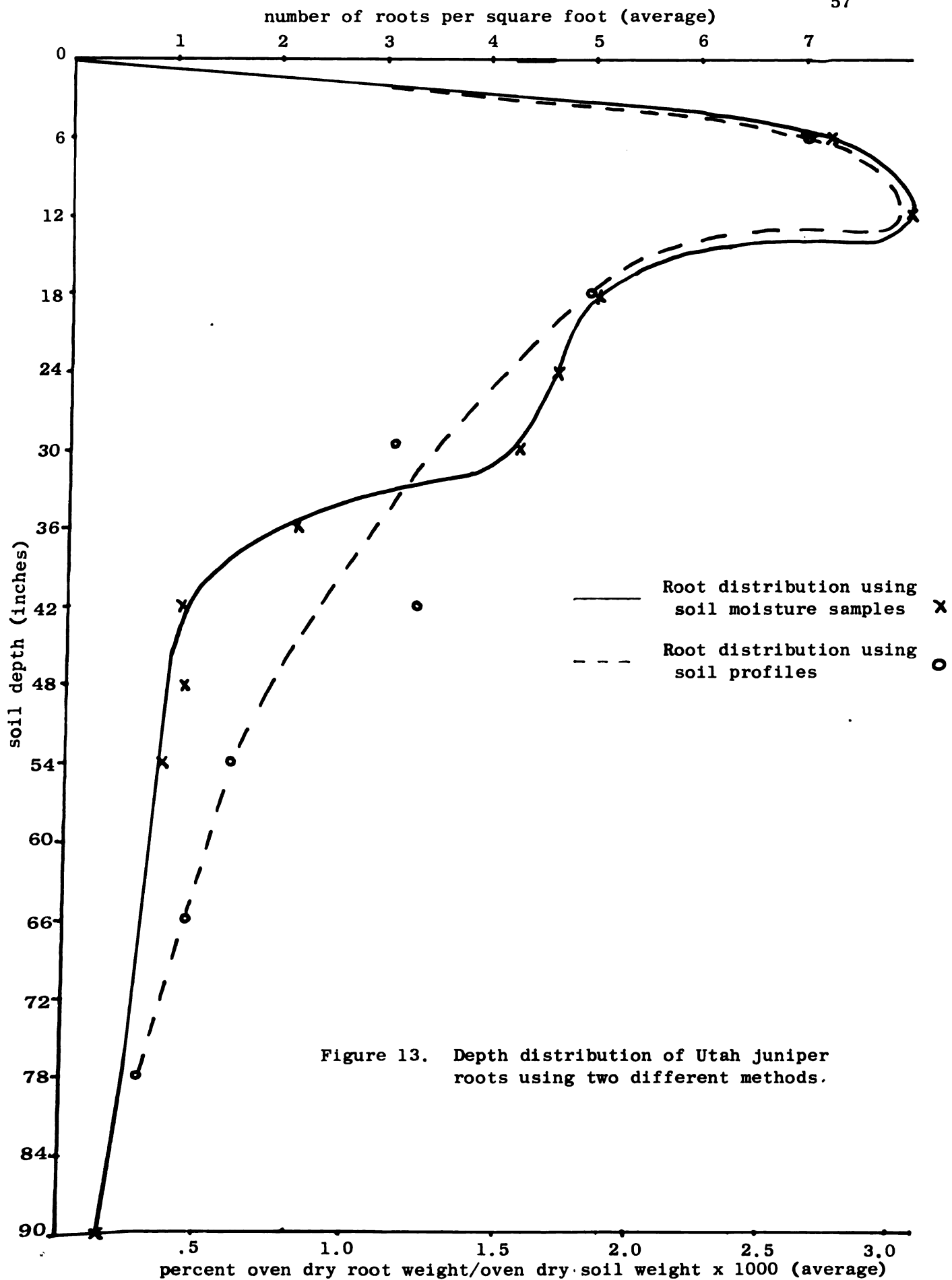


Figure 13. Depth distribution of Utah juniper roots using two different methods.



Figure 14. A representative profile of the study plots. Note the large concentration of roots in the upper three feet of soil. Refer also to Figure 8.

penetration, and soil moisture measurements reveal a rather consistent lack of water below 36 inches. By way of comment it has been the author's experience to find Utah juniper roots occupying rock crevices over 15 feet below the ground. Johnsen¹ reports Utah juniper roots as deep as 50 feet.

Soil Properties.

One of the most commonly found soils in the Utah juniper type on the Beaver Creek Watershed belongs to the tentatively correlated Springerville series.² The soils on the experimental plots have been identified as belonging to this series³. A tentative description of the Springerville series follows⁴:

Springerville Series

The Springerville series consists of brown, moderately well-drained to well-drained Grumusols that occur in the Reddish Prairie soils zone. They have developed in place over basalt lava and basalt cinders and bombs. They occur on smooth to slightly irregular surfaces under a sparse cover of vegetation including western wheatgrass, western yellow pine, juniper, and some brome grass.

These soils are associated with, and are similar to the McNary series, differing principally in having brown rather than dark-gray A₁

¹Private communication.

²Private communication with members of the soil survey party, Soil Conservation Service, which mapped this area in 1959.

³In collaboration with Milo James, State Soil Scientist, Soil Conservation Service, U.S.D.A.

⁴National Cooperative Soil Survey, U.S.A.

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horizons. Springerville soils are associated also with those of the Show Low and Elledge series but differ from them greatly in parent material and horizonation. The Show Low series is classified as Reddish Chestnut, and the Elledge series is a Planosol.

Soil Profile: Springerville Clay (virgin).

- | | | |
|-----------------|--------------|---|
| A ₁₁ | 0-2 inches | Brown (7.5YR 4/2) to dark-brown (7.5YR 3/2) clay; strong very fine granular structure; hard when dry, friable when moist, very plastic when wet, very sticky; few plant roots; noncalcareous; pH paste, 6.6; pH on dilution, 7.0; abrupt wavy boundary. 1½ - 4 inches thick. |
| A ₁₂ | 2-17 inches | Brown (7.5YR 4/2) to dark-brown (7.5YR 3.5/2) clay; weak, crude, very coarse prisms break to strong very coarse and coarse irregular angular blocks; extremely hard when dry, very firm when moist, very plastic, very sticky when wet; abundant roots; few very fine tubular pores; noncalcareous; pH of paste is 6.5 and, on dilution, 7.4; clear wavy boundary. 10 - 17 inches thick. |
| A ₁₃ | 17-30 inches | Brown (7.5YR 4/2) to dark brown (7.5YR 3.5/2) clay; strong very coarse and coarse irregular angular and subangular blocky structure; extremely hard when dry, very firm when moist, very plastic, very sticky when wet; common roots; many slickensides at angles of 5 degrees to 45 degrees from the horizontal; noncalcareous; pH of paste 6.5, on dilution, 7.4; clear wavy boundary. 9 - 15 inches thick. |
| C _{ca} | 30-43 inches | Brown (7.5YR 4/2) to dark-brown (7.5YR 3.5/2) clay; with common medium and fine white mottles due to lime segregations; massive; extremely hard when dry, very firm when moist, very plastic, very sticky when wet; few very fine roots; very strongly calcareous; pH of paste 7.7, on dilution 8.3; abrupt wavy or irregular boundary. 10 - 20 inches thick. |
| Dr | 43 inches | Hard, weathered basalt. |

Range in Characteristics: Depth to bedrock ranges from 18 to 60 inches but is dominantly between 30 and 50 inches. Occasional to many basalt cobbles occur on the surface and in the profile in places. Surface cracks ½ to 1½ inches across and 15 to 20 inches deep develop when

the soil is dry, but when the soil is saturated these are difficult to locate. Clay and stony clay types have been reported.

Drainage and Permeability. Runoff is very slow and permeability through the profile is very slow. When dry, water enters through cracks.

Vegetation. Occasional yellow pine, juniper, blue grama, western wheatgrass, and some black sage.

Use. Most of this soil is used for range. A limited area is cultivated and used for growing vegetables and small grain.

Distribution. This soil has been mapped to date in the vicinity of Show Low, Arizona.

Series Proposed. Navajo County Soil Survey area, Arizona, 1957. Springerville is the name of a town in Apache County, Arizona.

Type Location. in the NE $\frac{1}{4}$ of the NW $\frac{1}{4}$, SW $\frac{1}{4}$ Sec. 24, T9N, R22E. Arizona.

Determinations were made of color, pH, texture, upper plastic limits, bulk density, moisture at 20- and 60-cm tension and wilting point. Results are shown in Table 4, and techniques used described in Appendix 2. Profiles of three experimental plots are shown in Figure 15 to demonstrate the variability in depth, stoniness and C horizon which may be encountered in the field.

With summer and winter wet seasons of limited precipitation, two alternate periods of wetting and drying occur each year. Since most of the clay fraction is montmorillonitic, swelling and shrinking occur on a pronounced scale. Figures 16 and 17 illustrate the cracking which

Table 4. Average values of soil properties on study plots.

Depth in.	Texture							Number Samples	
	Sand		Silt		Clay				
	2.0-0.5		0.5-.005		Range		Fine Clay		
	mm	Range	mm	Range	mm	Range	mm		
percent									
0-6	9.4	4-16	27.4	22-34	63.2	50-72	60.0	48-66	16
6-12	6.5	4-12	26.1	22-32	67.4	58-72	64.5	56-70	11
12-24	6.4	0-10	23.2	18-28	70.4	66-80	66.8	60-78	16
24-36	7.5	0-12	21.8	18-32	70.7	66-74	67.2	64-74	13
36-48	8.0	4-12	21.2	18-28	70.8	64.74	68.0	60-72	8
									Number Samples
0-6	pH	Range	Color (Reddish Brown)						8
6-12	7.4	7.2-8.0	5YR 2/2 to 4/3 and 7.5YR 3/2						8
12-24	7.3	7.0-7.7	5YR 3/2 to 4/3 and 7.5YR 3/2						16
24-36	7.7	7.0-8.3	5YR 3/3 to 4/4						12
36-48	8.0	7.6-8.3	5YR 4/3 to 5/4						6
	8.1	7.9-8.3	5YR 4/3 to 5/4						
									Number Samples
0-6	Upper Plastic Limit		Number		Wilting Point				21
6-12	% O.D.	Range	% O.D.	Samples	Range				21
12-24	48.2	45-53	11.8	9	7-17				34
24-36	51.3	46-62	18.2	8	13-22				19
36-48	51.1	45-60	18.7	14	16-22				7
	52.8	47-57	20.2	15	17-22				
	53.5	50-56	20.6	3	18-21				

Table 4. (Continued).

Depth In.	Bulk Density : Range gms/cc	Saturation Pw : Pv % O.D.	20-cm Tension Pw : Pv % O.D.	60-cm Tension Pw : Pv % O.D.	Pore Space = 100%			Number Samples
					Non-Cap. Pores %	: Cap. Pores %		
0-3	1.12	0.88-1.22	51.2 55.8	46.3 50.4	44.5 48.5	13.1 86.9		14
3-6	1.24	1.13-1.39	41.9 51.5	39.7 48.9	36.1 47.6	7.6 92.4		7
9-12	1.31	1.24-1.41	38.7 50.4	36.3 47.2	35.7 46.5	7.7 92.3		6
12-24	1.35	1.25-1.44	38.3 50.2	36.7 48.2	35.2 47.2	6.0 94.0		17
24-36	1.38	1.32-1.45	36.4 49.0	35.2 47.4	34.0 46.8	4.5 95.5		12
36-48	1.36	1.29-1.41	39.3 53.4	37.0 50.2	36.3 49.4	7.5 92.5		4

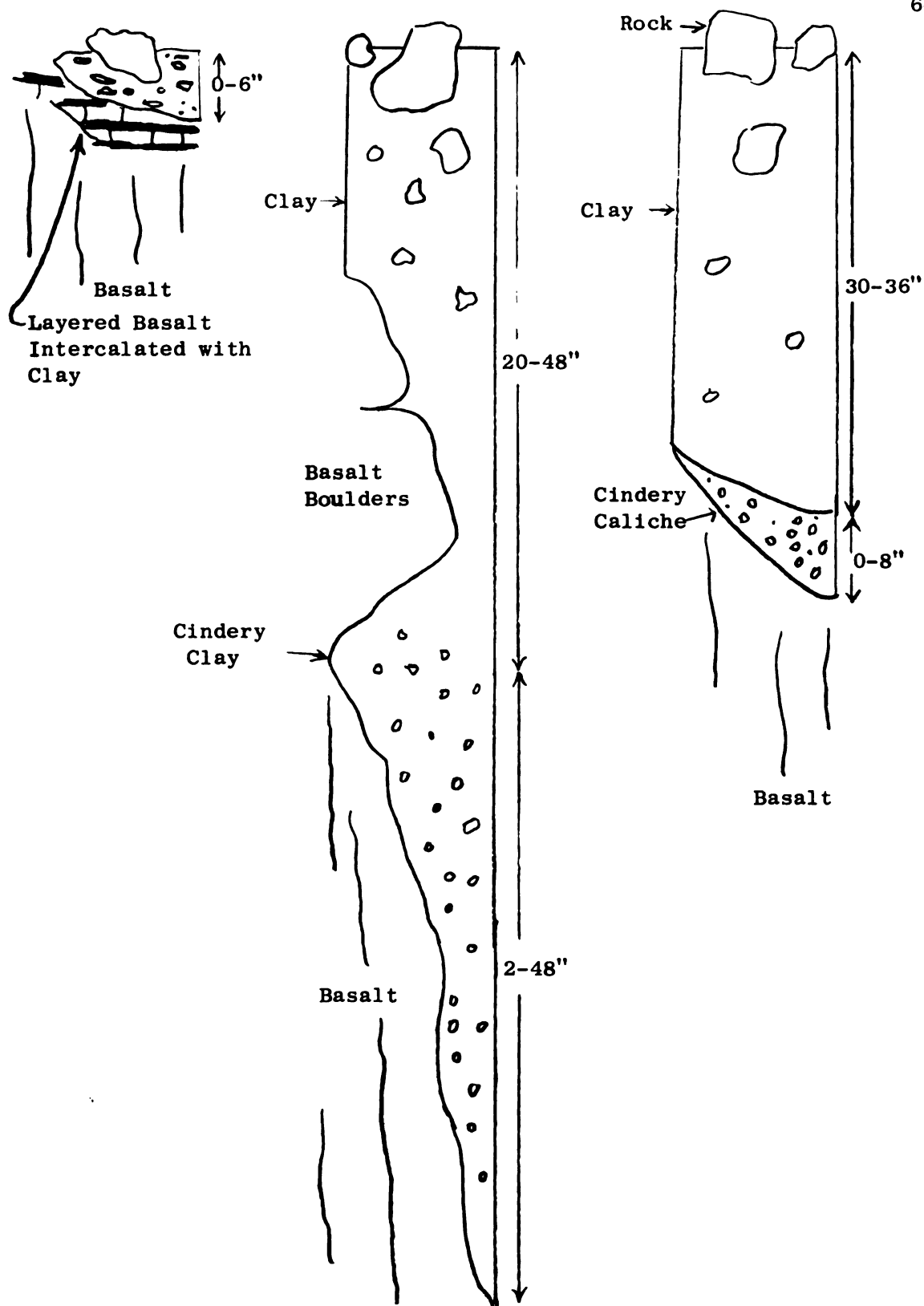


Figure 15. Range of soil profiles found on the study plots.

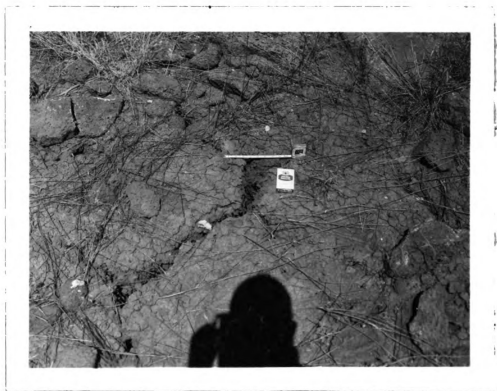


Figure 16. Soil cracks at the surface on plot 3 Light before soil pit was dug. July 15, 1958.



Figure 17. Soil cracks extending 24 inches deep to C_{ca} horizon of Springerville profile.

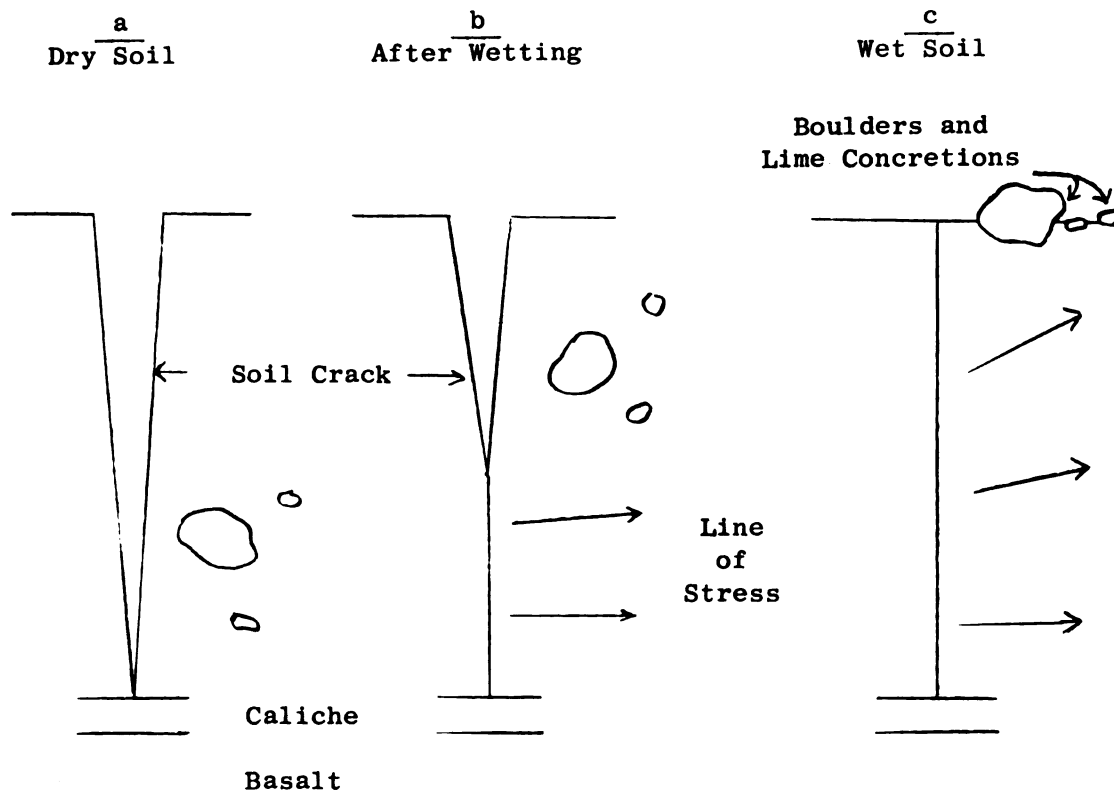
may penetrate to the C horizon. Figure 18 illustrates the self-swallowing action which ensues.

Soil cracks on the study plots were first observed to open during May. In order to gain some estimate of the extent of the cracks, a study was initiated in mid-July when soils were extremely dry and cracking most pronounced. A tape was laid along the ground down the 10 rows of stakes, so that 1,000 feet of line per plot was sampled. Whenever a crack intersected the line, its width was measured, and the location of the crack with respect to its occurrence in bare soil, next to a rock, or under litter was recorded. Cracks finer than 1/16 inch were not measured, nor could any estimate be made of cracks not reaching the surface.

Results are summarized below in Table 5. Plots 1 and 2 Light are omitted because their shallow depths do not permit a good comparison. It is worth noting that surface cracks larger than 1/16 inch are not found on plots 1 Medium and Heavy. Percent soil moisture on July 22 is included in Table 5 to suggest the reason for this difference.

Table 5. Soil cracking survey.

Plot	No. Cracks	Ave. Width In.	% Soil Moisture 7-22	% Occurrence		
				Soil	Rock	Litter
1M	0		21.8			
1H	0		21.3			
2H	54	.80	18.8	50	2	48
2M	209	.74	17.6	49	20	31
3M	227	.62	17.0	74	10	16
3L	249	.65	15.2	68	23	9
3H	297	.71	14.5	51	13	36



- a. Cracks have developed to the caliche layer.
- b. The cracks are beginning to close, with pressure due to swelling building up. The stresses leave a year-long record by the formation of "slickensides", or smooth cleavage planes. Soil clods will break along these planes. The nearer the surface, the more inclined.
- c. The crack has closed, but because coarse particles have washed in, will open along this weaker area next year. Rocks have been carried to the surface over many years.

Figure 18. Self-swallowing action of Springerville clay.

A comparison of percent litter (from Table 1) with percent cracks occurring under litter is also included in Table 5. The disproportionately greater percent cracks under litter suggests that this zone, directly beneath the crown, is more completely dried than that in the open. Such a result would be expected in accord with the usual distribution of tree roots.

The high percent of silt plus clay at the soil surface is very conducive to rapid sealing and low infiltration rates. This condition is exaggerated by summer storms of relatively high intensity and by the fact that vegetation cover is scant. The high percent of less than .002 mm clay and very low percent of non-capillary pores are good indicators that the soil is comparatively impermeable to downward or lateral flow of water. The soil cracks, then, seem to be the main avenue of rapid moisture penetration and subsequent movement of water within the soil body. That moisture can penetrate rapidly was demonstrated by the period September 12 to October 6 when about 6 inches of precipitation fell on the small, calibrated watersheds. This period included two storms, about 3.50 and 1.00 inches respectively, with maximum 10-minute intensities exceeding 4.00 inches per hour. Surface runoff measured at the flumes of the watersheds averaged only about 0.22 inch during this period.

Interception.

Part of the precipitation falling on a stand of Utah juniper never reaches the ground. It is retained by the leaves and bark of the plants and is then evaporated or absorbed by the foliage. This part of the

hydrologic cycle is called interception, and the amount of precipitation reaching the ground is referred to as throughfall. When the storage capacity of the leaves and bark is exceeded, water runs down the branches and trunk to the ground. This portion is referred to as stemflow. The objectives of this study were:

1. To estimate throughfall per storm as a function of gross precipitation per storm.
2. To determine which stand density measure is best related to total percent interception, and to define the nature of this relationship.
3. To estimate throughfall per storm as a function of gross precipitation per storm and the best measure of stand density.

The method used follows the formula:

$$\text{Net interception} = \text{Total precipitation} - (\text{Throughfall} + \text{Stemflow})$$

Measurements of precipitation, throughfall and stemflow were taken on the nine plots. Precipitation in the open was measured by two gages per plot. Open gages were so located that there was no foliage or other obstruction within 45 degrees of the vertical line above the gage. They were located as close to the plots as such natural openings permitted, and were placed on opposite sides of the plot.

Throughfall was measured by four precipitation gages per plot. These gages were placed at randomly selected locations, and moved to new random locations after each storm greater than 0.02 inch as measured in the open. All precipitation gages were set with the top of the collection funnel level and 10 inches above the average ground surface (See Figure 11).

Stemflow was measured on three trees per plot by means of collars. (See Figure 19) fitted to the stems. The individual trees were



Figure 19. Stemflow collars in place on two average size junipers. Five gallon cans were used to collect stemflow. As much as 25 gallons were collected from individual trees after a storm.

representative of those found on the plot as regards size, configuration and distance to adjacent trees. The following equation was used to convert pounds of stemflow from three trees per plot into equivalent inches of depth:

$$\text{Inches precipitation per plot} = .000006407 \times \text{number trees per plot} \times \text{pounds stemflow from three trees.}$$

Results.

Stemflow. Total stemflow for each plot is summarized in Table 6. Because of the relatively small contribution of stemflow, it was omitted from further interception analysis. It is interesting to note that stemflow begins somewhere between 0.25 and 0.30 inch rainfall. No stemflow was measured after snow storms, even those exceeding 1.00 inch water equivalent when temperatures the following day were well above freezing. Figure 20 shows interception of snow. No snow remains on the trees although several inches are on the ground. The more rapid loss of snow from crowns can be logically ascribed to greater evaporation opportunity through increased wind movement and lower albedo of dark foliage. Some snow also blows off.

It is also worth noting that the values of 0.25 to 0.30 inch for the point of stemflow beginning are higher than those generally reported by Kittredge (1948). This is probably attributable to the increased storage capacity created by shaggy bark.

Interception. Gross precipitation, interception and percent crown density using the spherical densiometer (%CD-D) were tabulated by plot, by storm and by individual precipitation gages. Thus, there

Table 6. Total stemflow and interception during the period of study.

Plot	Gross Precipitation	Stemflow		Percent Stemflow of Gross Precipitation	Inter- ception	Percent of Gross Precipitation
	in.	lb.	in.		in.	
1L	14.89	1,424	0.15	1.0	0.96	6.4
2L	15.65	644	0.09	0.6	0.28	1.8
3L	14.29	1,040	0.18	1.3	1.43	10.0
Ave.	14.94	1,036	0.14	1.0	0.89	6.1
1M	15.80	578	0.18	1.1	2.88	18.2
2M	14.83	871	0.44	3.0	2.53	17.1
3M	14.39	335	0.09	0.6	2.87	19.9
Ave.	15.01	595	0.24	1.6	2.76	18.4
1H	15.79	423	0.22	1.4	3.07	19.4
2H	15.03	549	0.57	3.8	3.58	23.8
3H	14.22	619	0.46	3.2	3.06	21.5
Ave.	15.01	530	0.42	2.8	3.24	21.6
Gd. Ave.	14.99	720	0.27	1.8	2.30	15.3



Figure 20. Interception of snow by Utah juniper. Notice that no snow remains on the trees, while several inches is on the ground. No stemflow occurred from this storm.

were 136 measurements of interception per plot, 408 per density class, and 1204 total.

The data show that Utah juniper intercepts amounts of precipitation according to the density of the stand. These amounts were totaled for the period of study. They were then averaged by stand density classes and for all densities combined as shown in Table 6.

Throughfall as a Function of Gross Precipitation. Individual regressions of throughfall ($\hat{Y}$) over gross precipitation per storm (X) were computed for each plot. They are listed below with appropriate correlation coefficients:

<u>Plot</u>	<u>Regression</u>	<u>Correlation Coefficient</u>
1L	$\hat{Y} = .9445X - .0093$	.997
2L	$Y = .9907X - .0050$	.999
3L	$Y = .9723X - .0293$	.996
1M	$Y = .9281X - .0513$	.988
2M	$Y = .9488X - .0440$	.993
3M	$Y = .7962X - .0020$	.990
1H	$Y = .9088X - .0509$	.991
2H	$Y = .7568X - .0005$	.995
3H	$\hat{Y} = .8897X - .0434$	.996

Analysis of variance was used to test variance due to regression. The "F" values for variance due to regression were all significant to 0.1 percent. The "a" term was never significantly different from zero.

An analysis of covariance was run on the individual regressions, first collectively, then by density classes, and finally within density classes (See Table 7). Individual regressions were then plotted by density classes. It was observed that nearly all of the variation in throughfall could be accounted for by regression. Since each of the

Table 7. Analysis of covariance¹: Using regressions of throughfall over gross precipitation per storm.

Source	d.f.	$\sum d^2_{yx}$	MSq.	F
<u>Between All Plots</u>				
Within	1206	21.1634	0.0175	
Reg. Coef.	8	2.6643	0.3330	19.03**
Common	1214	23.8277	0.0805	
<u>Between Light and Medium Plots</u>				
Within	808	13.2584		
Reg. Coef.	1	0.5380	0.5380	31.46**
Common	809	13.7964	0.0171	
<u>Between Medium and Heavy Plots</u>				
Within	808	19.3997		
Reg. Coef.	1	0.1113	0.1113	4.62*
Common	809	19.5110	0.0241	
<u>Within Light Density Plots</u>				
		1 vs 2		9.34**
		1 vs 3		3.09 Non. Sig.
		2 vs 3		1.36 Non. Sig.
<u>Within Medium Density Plots</u>				
		1 vs 2		0.56 Non. Sig.
		1 vs 3		14.18**
		2 vs 3		25.13**
<u>Within Heavy Density Plots</u>				
		1 vs 2		21.18**
		1 vs 3		1.97 Non. Sig.
		2 vs 3		37.06**

¹After Snedecor.

regression equations describes a "tight-fitting" curve, small differences in slopes of the curves were predictably shown to have significance when tested by covariance.

An apparently puzzling problem arose when differences within density classes Medium and Heavy were found to exceed differences between them. Inspection of the plotted regressions showed plots 3 Medium and 2 Heavy accounting for the large differences within density classes. From Table 6 it is readily apparent that differences in percent crown density within a stand density class do not provide an explanation. The explanation was provided by examination of the storm-size classes sampled. No storm sizes between 1.17 and 3.35 inches, and only two storms of about 1.00 inch, occurred. Much of the total variation in throughfall could be accounted for by variation in these large storms. Plots 3 Medium and 2 Heavy intercepted appreciably more precipitation during these few large storms than the other plots. Additional sampling of large storm sizes would probably "iron out" the slope differences within the density classes.

Determining the Best Stand Density Measure in Relation to Total Percent Interception. Total percent interception was computed for each of the nine plots by the formula:

$$\text{Tot. \% Interception} = \left(1 - \frac{\text{Tot. Throughfall}}{\text{Tot. Precip.}} \right) \times 100$$

Regressions of total percent interception over each of the eight stand density measures used on the nine plots were computed. They are listed in Table 8 with appropriate correlation coefficients, "F" values due to regression, and standard errors of regression.

Table 8. Regressions of stand measures of density and percent interception.

	Independent Variable	Regression	"r"	"F"	Standard Error for 1958-59 PPT*	
					%	inch
1.	Percent crown density (densiometer)	$\hat{Y} = 0.38x \neq 0.37$	.95	74.6	2.37	0.36
2.	Percent crown density (line intercept)	$Y = 0.36x \neq 1.90$	.87	22.9	3.91	0.59
3.	Number trees higher than 3 feet	$Y = 0.26x \neq 3.19$	.81	13.03	4.77	0.72
4.	Number trees higher than 6 feet	$Y = 0.31x \neq 4.65$	.87	22.60	3.91	0.59
5.	Number trees higher than 10 feet	$Y = 0.48x \neq 4.75$	.91	34.90	3.30	0.50
6.	Total live crown length of trees over 3 feet	$Y = 0.026x \neq 3.81$	.88	25.18	3.77	0.57
7.	Total live crown length of trees over 6 feet	$Y = 0.027x \neq 4.49$	.90	29.25	3.55	0.53
8.	Total live crown length of trees over 10 feet	$\hat{Y} = 0.035x \neq 4.71$	.93	43.19	3.01	0.45

*15.0 inches.

Table 8 shows that the stand density measure best related to total percent interception is percent crown density as measured by the spherical densiometer. Total length of live crown for respective tree heights is consistently better related to total percent interception than number of trees. However, number of trees higher than 10 feet shows a better relationship than total length of live crown on trees higher than 3 and 6 feet. Percent crown density as measured by the Line Intercept method shows no advantage over number of trees higher than 6 feet.

In terms of inches of water, the standard errors for the various stand density measures for the year of observation are listed in Table 8. For practical purposes the number of trees higher than 10 feet could most easily be field sampled with little loss of precision as compared to percent crown density by the spherical densiometer (%CD-D). Whether the relationship between number of trees higher than 10 feet and total percent interception remains the same for years having different precipitation patterns is a moot point. Most likely the relationship will change, but only to a small degree.

Throughfall as a Function of Gross Precipitation Per Storm and the Best Stand Density Measure. A multiple regression was computed using the following variables:

X_1 = Gross precipitation per storm.

X_2 = (%CD-D)² at the random location where throughfall was measured for each storm.

Y = Throughfall measured at each random location per storm.

Results and tests are shown in Table 9 and plotted on Figure 21. While the relationship between gross precipitation and throughfall is linear,

Table 9. Throughfall as a function of $(\%CD-D)^2$ and gross precipitation per storm.

Multiple Regression Equation.

$$\hat{Y} = 0.026 + 0.907X_1 - 0.208X_2$$

$\hat{Y}$ = Estimated Throughfall

X_1 = Gross Precipitation per Storm

X_2 = $(\%CD-D)^2$

Overall "F" Test.

<u>Source</u>	<u>d.f.</u>	<u>MSq</u>	<u>F</u>
Total ($\sum y^2$)	1077		
Regression ($\sum Y_1^2$)	2	184.5800	9,977.30
Deviation ($\sum y_1^2$)	1075	0.0185	

Standard Partial Regression Coefficients.

$$b'Y1.2 = 0.970$$

$$b'Y2.1 = 0.098$$

Confidence Interval.

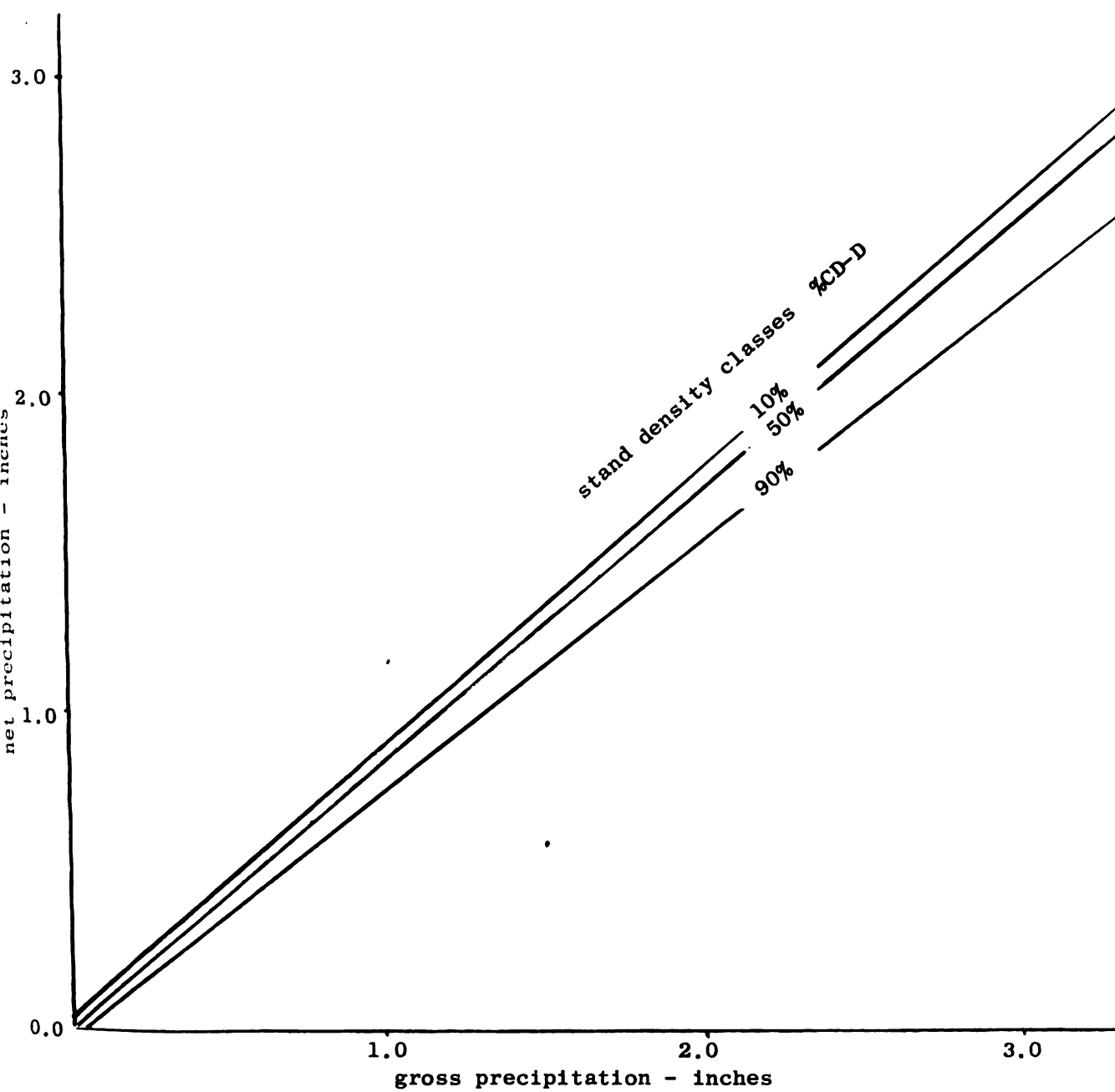
+ or - 0.0107 inch at 1 percent probability.

"t" Test for Regression Coefficients.

$t_1 = 141.72^{**}$ (gross precipitation)

$t_2 = 14.15^{**}$ (the square of percent crown density as determined by a spherical densiometer)

Figure 21. Net precipitation as a function of Gross precipitation and percent crown density squared ($\%CD-D$)²

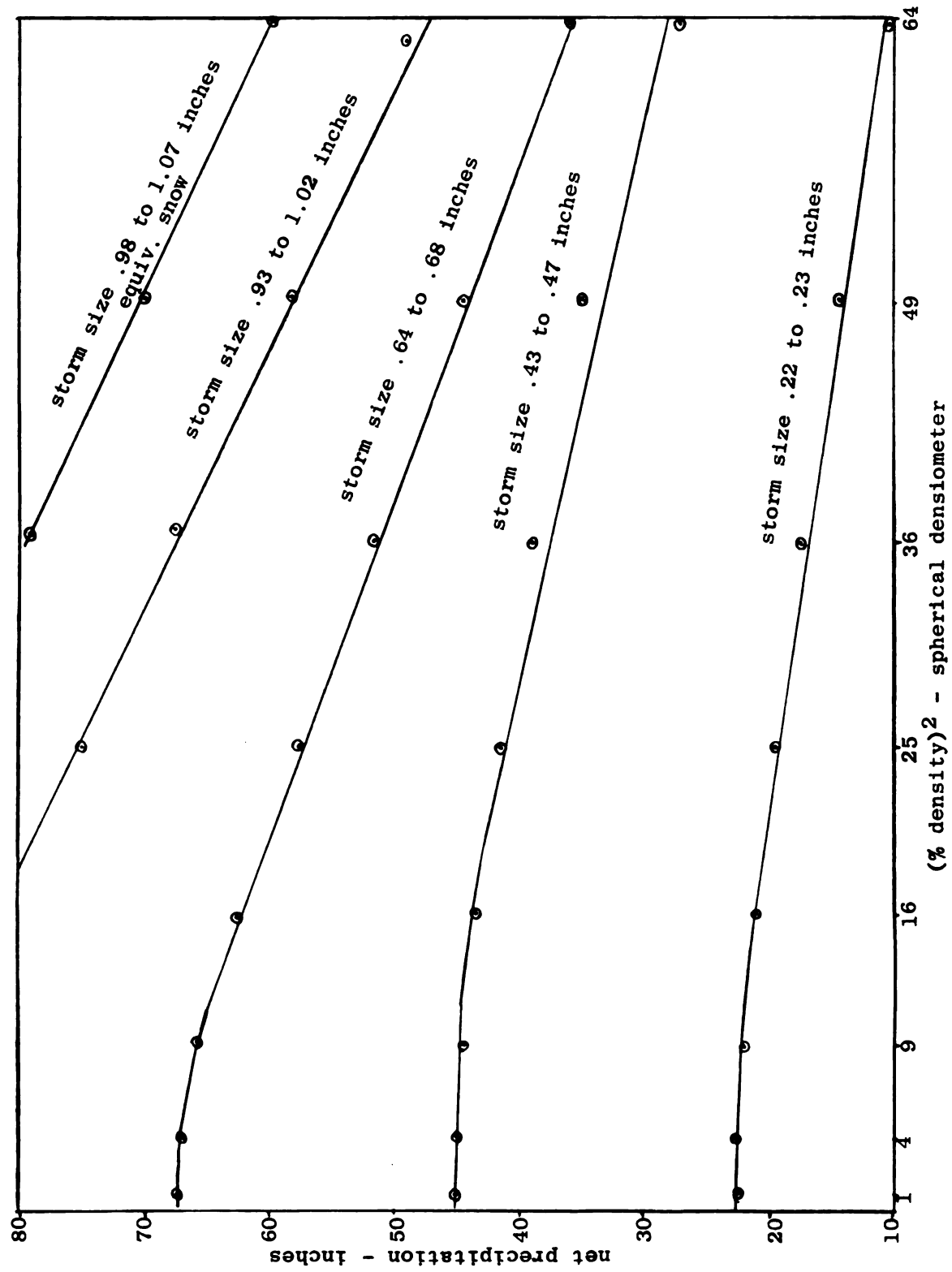


the relationship between percent crown density by the spherical densiometer (%CD-D) and throughfall was unknown. Throughfall over percent crown density by the spherical densiometer (%CD-D) was then plotted for storm-size intervals of .22 to .23 inch; .43 to .47 inch; .64 to .68 inch; .93 to 1.02 inches; and finally .98 to 1.07 inches water equivalent for snow only. Freehand curves were then plotted according to various functions of percent crown density by the spherical densiometer (%CD-D) and throughfall. Perhaps the function that makes most sense is shown on Figure 22, where throughfall in inches is plotted over the square of percent crown density by the spherical densiometer (%CD-D). As the crown density of a stand increases, the incidence of vegetative parts overlapping each other increases - a three dimensional effect. The instrument mirror, however, only reflects a two dimensional image of the crown. The real effect then, is a geometric increase in vegetative matter being recorded arithmetically by the mirror.

Examination of the standard partial regression coefficients reveals that gross precipitation per storm contributes about ten times the amount of variance due to regression as percent crown density by the spherical densiometer (%CD-D). The limited role played by percent crown density by the spherical densiometer (%CD-D) was partly explainable by examining the frequency with which throughfall exceeded gross precipitation. This situation is simply explained by the fact that water tends to collect near the twig ends, the familiar "crown drip."

As Table 9 shows, both of the regression coefficients are significant at 1 percent; however, it must be remembered that only a few large storms have been sampled as well as only one year's precipitation pattern..

Figure 22. Net precipitation related to $(\% \text{ density})^2$ as measured by the spherical densiometer.



Surface Runoff, Depression Storage, Subsurface Flow and Percolation.

Surface runoff, depression storage, subsurface flow and percolation are important components of the "water cycle." However, because there were virtually no previous records of these components in the juniper type of Northern Arizona, and because the total amount of water involved in these components was small during the period of study, only a short discussion of each follows.

Surface Runoff. Relative amounts of surface water movement were measured on each main and check plot by four randomly located 2 x 3 foot subplots, or twelve per density class and four on the check plot (See Figures 23 and 24).

In order to account for some of the expected variability in surface water movement between the 40 subplots, the following factors were measured on each subplot:

1. Surface cover was measured using a grid with 100 sampling points. Percent rock, bare ground and litter were computed. Percent green cover and litter depth were estimated ocularly.
2. Slope was measured with a transit and rod, and percent slope computed.
3. Soil cracking was estimated ocularly to be extensive, moderate or absent.
4. Crown canopy was measured with a spherical densiometer at each corner of the plot, and average percent computed.

Additionally, at the end of the study period the storms with the smallest total amount and lowest intensity which produced surface water movement on any of the subplots was identified. All storms having higher total amounts or higher maximum 10-minute intensities were then tabulated from the recording precipitation gage charts.



Figure 23.. A 2 x 3 foot subplot used to determine surface water movement on a Light density plot. The collection can holds about 40 pounds of water when full. It overflowed after a 3.50 inch storm on September 12.



Figure 24. A subplot on a Heavy density plot. No water was ever produced from this subplot with 100 percent litter cover about $1\frac{1}{2}$ inches deep.

Surface water movement from each plot for each storm was then converted to inches of water. The original intention was to run a multiple regression using the factors just discussed. However, after consultation¹, this analysis was not undertaken due to the preponderance of zero runoff values. A suggestion of the influence of litter and rock is given in Figures 25 and 26, where surface water movement in inches is plotted against percent litter and rock respectively for the storm of September 12², the only storm suitable for regression analysis. There appears to be an increase in surface water movement with a decrease in percent litter and an increase in percent rock.

The total amount of surface water movement was then grouped by stand density classes using all storms except that of September 12 (storm number 18) when many of the collection cans on the Light density plots overflowed. The data is shown in Table 10 along with supplementary data on average soil depth and number of storms producing surface water movement. The data suggests that surface water movement decreases with an increase in stand density and an increase in soil depth.

The relative amounts of surface water movement by stand density class were in the order of 1.5 to 1.0 to 0.4 going from Light to Medium to Heavy density. In order to get a realistic estimate of actual surface runoff from the plots, the above ratios were related to average

¹Jacob Kovner, Statistician, Rocky Mountain Forest and Range Experiment Station.

²Prepared by Mrs. Peterson, Assistant Statistician, Rocky Mountain Forest and Range Experiment Station.

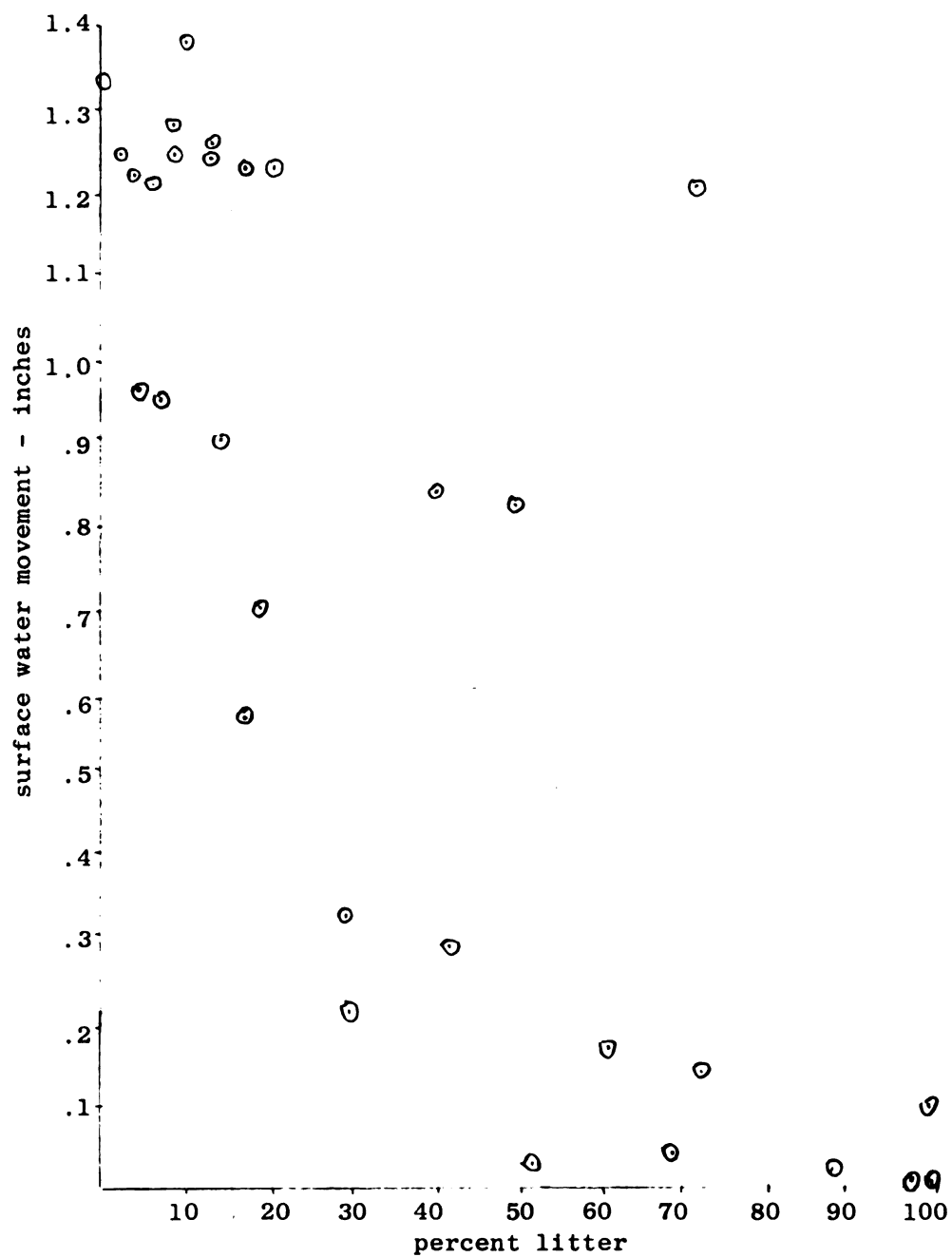


Figure 25. The influence of juniper leaf litter on surface water movement.

Storm of September 12 to 13, 1958
3.35 to 3.92 inches.

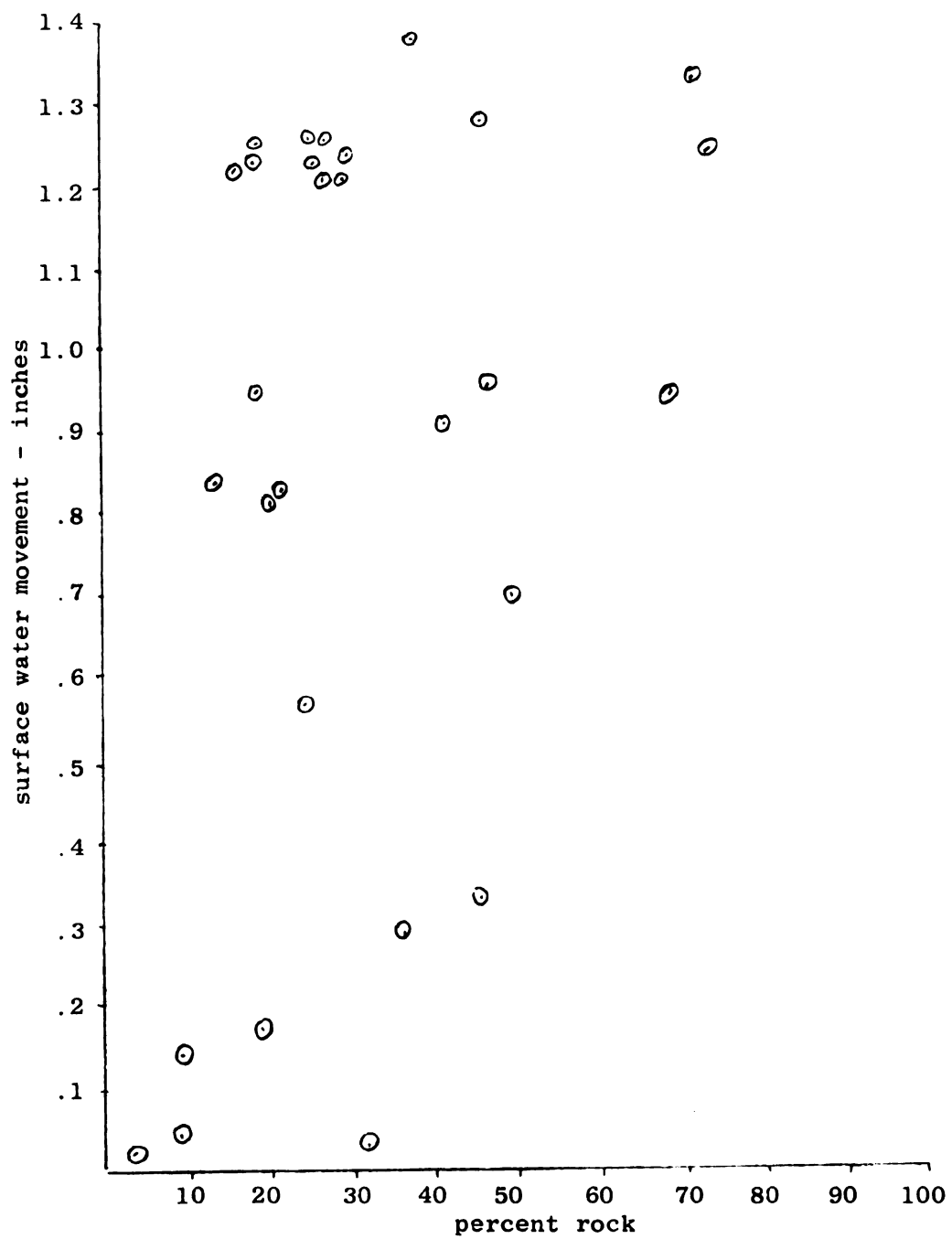


Figure 26. The influence of rock cover on surface water movement.

Storm of September 12 to 13, 1958.
3.35 to 3.92 inches.

Table 10. Surface water movement excluding storm number 18, for the period of study.

Plot	Surface Water	Number Storms	Average	CD-D
	Collected	Producing Surface	Soil Depth	
	in. equiv.	Water Movement	in.	%
1L	0.88	7	6.0	16.2
2L	1.20	5	6.0	9.9
3L	0.10	1	21.1	23.7
Ave.	0.73	4.3	11.0	16.6
1M	0.64	3	48.0	46.5
2M	0.56	3	32.6	39.9
3M	0.16	2	48.0	39.8
Ave.	0.42	2.7	42.9	42.1
1H	0.24	1	48.0	58.6
2H	0.14	1	37.6	60.7
3H	0.14	1	30.0	56.9
Ave.	0.17	1	38.5	58.7

surface runoff as measured by the water-stage recorders on the small, calibrated watersheds. Surface runoff from these watersheds averaged a total of about 0.22 inch during the entire period of study, 0.11 inch occurring during sampling periods 9 and 10 (September and October). The value 0.11 inch was assigned to the Medium stand density class, typical of the stand density on the small, calibrated watersheds. The value 0.11 inch was then multiplied by the appropriate index of either 1.5, 1.0 or 0.4 to obtain realistic surface runoff values for periods 9 and 10.

Light density plots 1 and 2 were given individual treatment for September, 1958. Since the soil depth of these plots is about 6 inches, and they were very dry prior to storm number 18, they could absorb only about 1.50 inches of water. Precipitation was 3.36 and 3.92 inches on Light density plots 1 and 2 respectively for that storm. Therefore, about 1.86 and 2.42 inches were unaccounted for on these plots. Two recording precipitation gage charts both show that the storm lasted about fifteen hours, and that about one-half of the total amount occurred as high intensity bursts, likely to cause water to run off a saturated soil. Accordingly, one-half of the 1.86 and 2.42 inch amounts was assigned to surface runoff, the other half to percolation.

Depression Storage. This quantity was negligible for the year, since the plots were located on uniform slopes permitting fairly rapid drainage. Observations taken on the plots immediately after storms showed no free water surfaces of any size.

Subsurface Flow. Since total flow on the small, calibrated watersheds was only 0.22 inch, and since the bulk of it occurred as sharp

peaks following two intense summer storms, subsurface flow was assumed to be negligible.

Percolation. Some percolation to groundwater may have occurred during the year through large soil cracks or otherwise. The soil never reached field capacity on any of the sampling dates, and was very dry during most of the year. It is very doubtful that appreciable amounts of water could have percolated to the underlying basalt formation.

Soil Moisture.

The importance of soil moisture can hardly be overstated in relation to watershed management. The soil profile has a definite storage capacity for water, and the amount of surface runoff for a given storm will be governed in part by the degree to which this capacity is used prior to the storm. The amount of available water in the soil profile will also govern the amount of water evaporated from the soil and transpired by plants. The degree of susceptibility to compaction and erosion at a given time is influenced to a great degree by the amount of water in the soil.

To account for the disposition of precipitation using the "water balance" method, and to explore the nature of soil moisture trends, periodic measurements of changes in soil moisture were made. Inches of water stored in the soil at any sampling date was computed by the general formula:

$$\text{Inches of water} = \frac{P_w \times P_a \times d}{100}$$

P_w is percent moisture, oven dry basis

P_a is bulk density

d is soil depth in inches

Percent Moisture (Pw). Percent moisture samples by six-inch intervals were taken monthly from April, 1958, to April, 1959, at four randomly selected locations on each plot (See Figure 27). Field sampling and laboratory procedures are well standardized. In order to sample to parent rock it was often necessary to reject two to ten samples, in which case samples were taken at locations resembling the original random point. Appendix 3 shows average Pw by sampling date, by plot and by 6-inch depth interval. Appendix 3a outlines the procedure used to correct Pw for rock included in the samples.

Bulk Density (Pa). Bulk density samples were taken by the following 3-inch depth intervals to bedrock:

0-3	9-12	21-24	33-36	45-48	57-60
3-6	15-18	27-30	39-42	51-54	

Samples were taken at 4 representative plots, two pits per plot. Field sampling and laboratory procedures are described by Garey (1957) and Hoover, et al. (1954). Bulk density values and supplementary data for the 4 plots are shown in Appendix 4. The procedure for computing average bulk density values by 6-inch depth intervals for each plot is discussed in Appendix 4a.

Soil Depth (d). Average soil depth to parent rock for an entire plot was computed from soil moisture samples taken with the Veihmeyer tube. Only samples which gave every indication of striking parent rock were used. Even these can be misleading, so the sampling error would tend to produce an average plot depth less than actual. Appendix 5 shows the number of samples, range of depth, mean depth, confidence limits and standard error for each plot.



Figure 27. Soil sampling with a Veihmeyer tube in a dry clay soil using a soil jack. Separate tube points were used depending on soil moisture, depth and stoniness. When the soils were dry, as they usually were, the tube could be driven about 1 inch for every blow with the 15-pound driving hammer.

Inches of Water. An actual example of the inches of soil water computed for plot 2 Medium density on April 22, 1958, is shown below:

<u>Depth</u>	<u>Average Moisture %</u>	<u>Average Bulk Density</u>	<u>Average Moisture in.</u>
0- 6	25.6	1.15	1.77
6-12	34.5	1.23	2.55
12-18	31.7	1.28	2.43
18-24	31.8	1.32	2.52
24-30	32.3	1.35	2.62
30-32.6	33.5	1.37	1.19
			<u>13.08</u> Total

Appendix 6 shows inches of soil water and differences in inches of soil water by sampling date, by plot and by 6-inch depth interval.

Results.

Relation of Stand Density to Water Consumption. An attempt was made to relate some stand density measure to soil moisture use. The logical periods between sampling dates to compare were those in which water was readily available to the plants. It is generally known that when soil moisture closely approaches wilting point further withdrawal is exceedingly slow, and differences in soil moisture use due to differences in plant density are not apt to be measurable.

Determination of the point at which soil moisture depletion rate decreases markedly was of primary concern. The period from April 24, 1958, to July 23, 1958, was selected as suitable for studying depletion rate. Only 0.60 inch of rain fell during the 89 days of the test period. Only plots having an average depth of over 30 inches were selected. Average percent moisture was first computed by 6-inch intervals for sampling dates 4, 5, 6, and 7. Six plots, 1, 2 and 3 Medium and

Heavy density, were used for depth intervals from 6 to 30 inches.

Plots 1 Medium and Heavy density were rejected for the 0-to 6-inch interval because they showed excessive sampling variation. Values are shown in Table 11. These values were then plotted to obtain a field estimate of wilting points. Table 11 also shows average percent moisture at field capacity, average bulk density and average available water-holding capacity by 6-inch intervals.

Using the estimated wilting points, average inches of available water was then computed for each of the four sampling dates. Average percent available water of average total available water-holding capacity was computed for each sampling date by 6-inch intervals and plotted. It was observed that the rate of available water withdrawal is nearly constant from about 65 percent down to about 5 percent, and nearly equal for all 6-inch intervals. The shape of the depletion curve is generally in agreement with Penman's concept (Smith, 1959).

The selection of periods which offered the best chance for measuring differences in soil moisture use between stand density classes presented some difficulty. The winter periods were rejected because of the traditionally low evapotranspiration rates. Differences would be too small. The September and October periods were rejected because they were periods of soil moisture accretion. The periods from April 24 to June 20, 1958, and March 3 to April 23, 1959, seemed ideal because: available soil moisture was above 5 percent of total; no surface runoff occurred to complicate matters; precipitation was scanty; no precipitation occurred at least 10 days before the sampling dates, thereby

minimizing sampling variation; interception effects were also minimized because of the small amount of precipitation.

In the first analysis, only the Medium and Heavy density plots were compared, since there remained but one Light density plot with any appreciable soil depth. Analysis of variance showed no significant difference between the Medium and Heavy density plots for either period. The following figures indicate the size of the differences:

<u>Depth</u> inches	<u>Period</u>	<u>Days</u>	<u>Average Inches</u> <u>Water</u> <u>Used Per Plot</u>		<u>Average Inches</u> <u>Water Used</u> <u>Daily Per Plot</u>	
			Medium	Heavy	Medium	Heavy
0-30	4/24 to 6/20/58	58	4.02	3.81	0.069	0.066
0-30	3/3 to 4/23/59	48	1.39	1.31	0.029	0.027
	Total	106	5.41	5.12	0.051	0.048

In the second analysis a comparison was made of inches of soil moisture withdrawal in 24 inches of soil for the same sampling periods. In this instance, only single plots at replication 3 were compared. These plots are located within 100 yards of each other; their soil properties are nearly identical; and they all received the same amount of precipitation. Values for the 18 to 21.1 inch depth interval on plot 3 Light density were extended proportionately to 24 inches. Results are shown below:

<u>Depth</u> inches	<u>Period</u>	<u>Days</u>	<u>Average Inches</u> <u>Water Withdrawn</u>		
			Light	Medium	Heavy
0-24	4/24 to 6/20/58	58	2.98	3.19	3.23
0-24	3/3 to 4/23/59	48	0.99	0.99	0.99
	Total	106	3.97	4.18	4.22
	Average Daily		0.037	0.039	0.040

It is apparent that total, period and daily differences are so small as to be negligible, and may easily be attributed to sampling variation.

Apparently evaporation alone during the April to June and March to April periods was able to keep pace with combined evaporation and transpiration of soil moisture in 24 to 30 inches of soil. Soil cracking would certainly contribute to making such a supposition possible.

Evapotranspiration of Soil Moisture.

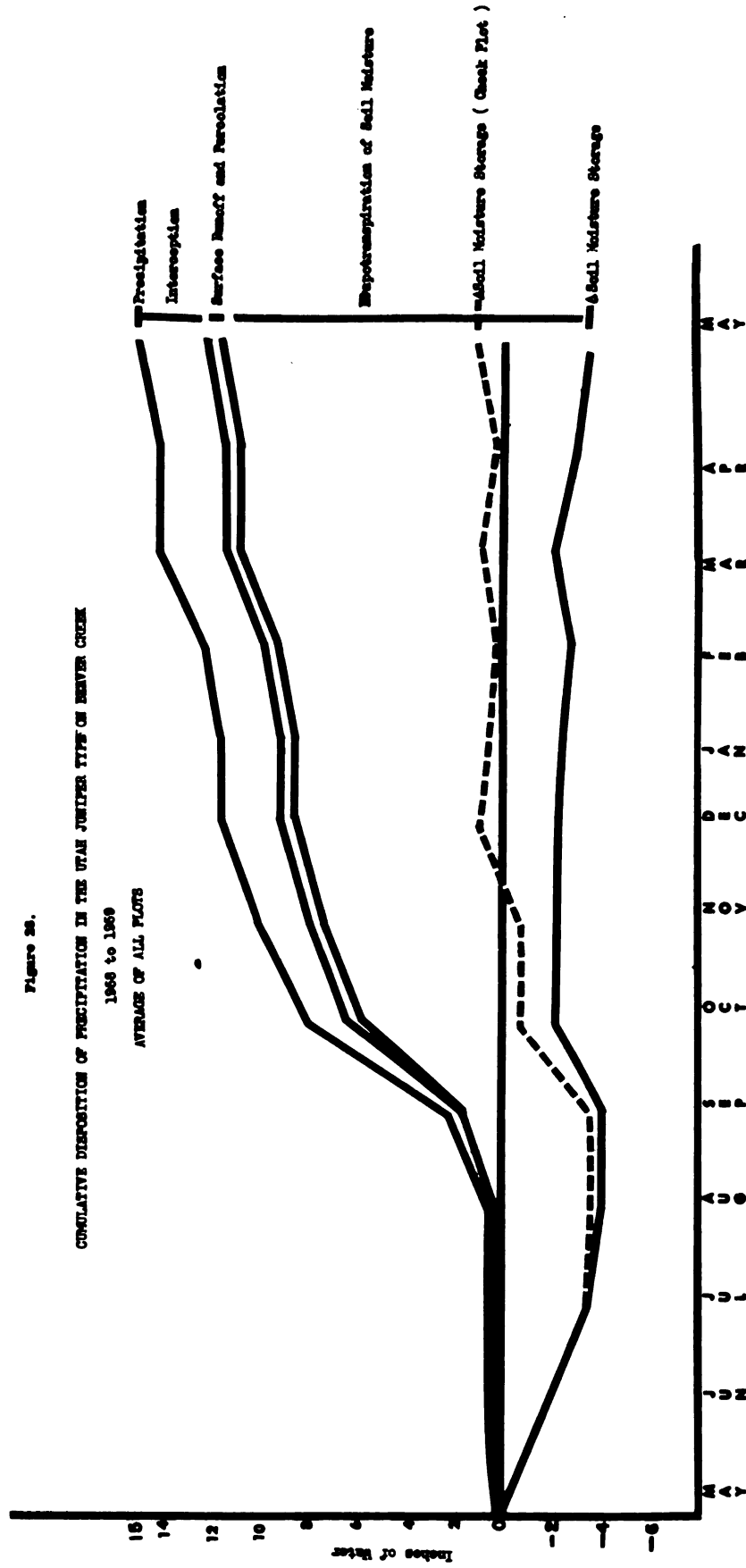
Evapotranspiration of soil moisture was computed from the formula for the "water balance" method. Values are summarized in Appendix 7 and average values for all plots shown in Figure 28.

Inspection of the data showed that values ranged from 12.74 to 18.17 inches for the year. Since these differences existed, the factors responsible for them were studied. The largest and most important differences in factors associated with differences in evapotranspiration from the soil were stand density, net precipitation and average soil depth. Interception differences were shown previously to be a function of stand density and differences in net change in soil moisture storage are shown to be largely a function of average soil depth by the following regression:

$$Y = 0.22 + .093X$$

The regression equation is significant to 1 percent; the regression coefficient significant to 0.5 percent; and the standard error of regression 0.62 inch net soil moisture change. There were obvious differences in surface water movement and percolation between the plots, but these differences were both small and, in a sense, artificial, hence were not included in the analysis.

The selected factors presented a rather puzzling picture at first because they were interrelated. The following correlation



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coefficients suggest the nature of the complexity. Values used for evapotranspiration from the soil and net precipitation were one year totals.

<u>X₁ Variable</u>	<u>X₂ Variable</u>	<u>"r" Value</u>
Et(s)	%CD-D	.5350
Et(s)	Ave. soil depth	.8447
Et(s)	Net precipitation	-.2417
%CD-D	Ave. soil depth	.8100
%CD-D	Net precipitation	-.8067
Ave. soil depth	Net precipitation	-.6548

In order to test the independent effect of percent crown density using the spherical densiometer (%CD-D) average soil depth and net precipitation on evapotranspiration from the soil, a multiple regression was computed with evapotranspiration from the soil as the dependent variable. The following regression coefficients were obtained:

		<u>"b"</u>
X ₁	%CD-D	-.00105
X ₂	Ave. soil depth	.13655
X ₃	Net precipitation	.77485

A "t" test showed that the regression coefficient for percent crown density by the spherical densiometer (%CD-D) was not significant. This result is not surprising in view of the fact that only 15 inches precipitation occurred during the year of study. Little chance was given for an expression of soil moisture demands by different stand densities. Indeed, evaporation alone from bare soil could well exceed 15 inches.

A new multiple regression, using only average soil depth and net precipitation, was then computed with evapotranspiration from the soil again as the dependent variable:

$$\hat{Y} = 1.15 + .1360X_1 + .7819X_2$$

The standard error for the whole regression was 0.68 inch, with an "F" value of 27.8, significant at 1 percent. The "t" values for regression coefficients b_1 and b_2 were 7.23 and 3.28, significant at 1 percent and 5 percent respectively.

Partial correlation coefficients were then computed between average soil depth and evapotranspiration from the soil, holding net precipitation constant, and between net precipitation and evapotranspiration from the soil, holding average soil depth constant. The partial correlation coefficients were .9358 and .7698 respectively, both significant at 1 percent.

It appears then that average soil depth is a better predictor of evapotranspiration from the soil than net precipitation. This conclusion makes sense when the effect of average soil depth on net precipitation is considered. As shown previously, the "r" value for percent crown density by the spherical densiometer (%CD-D) and average soil depth is .8100; e.g., the deeper the soil, the greater the amount of crown volume. And, the greater the volume of crown, the less the net precipitation - "r" equals -.8067. The indirect effect of average soil depth on net precipitation is given by the "r" value of -.6548. Thus, net precipitation is dependently related to average soil depth.

It should be stressed immediately that the conclusion, "Average soil depth is a better predictor of evapotranspiration from the soil

than net precipitation.", applies only to situations in which other factors are held nearly constant between sites, and in which full expression of soil moisture use by different stand densities is restricted. It is quite likely that the above conclusion applies to total precipitation below 15 inches, since soil moisture use according to stand density would probably be restricted, and since differences in net precipitation between sites would be correspondingly smaller and have less effect on evapotranspiration from the soil.

It also seems logical that the relationship between soil depth and evapotranspiration from the soil depends to a great extent on differences in net soil moisture storage between the first and last determinations - the greater the difference, the greater the effect. However, given the situation where first and last readings were equal, and all differences in evapotranspiration from the soil due to differences in net precipitation, soil depth would still be important due to its indirect effect on net precipitation.

The Check Plot.

Average inches of water in 30 inches of soil was computed for the Medium and Heavy density and check plots at replication 3. Initial inches of water on June 20, 1958 in the Medium and Heavy density plots was adjusted to that of the check plot. The check plot was cleared in mid-June when nearly all soils were slightly above wilting point. By April 23, 1959 an average difference of 3.40 inches was measured between the check and Medium and Heavy density plots. This difference very likely would have been accentuated had not the winter period

between November and March been very dry. Less than 4.00 inches of precipitation occurred between November 1 and March 31, the usual period of soil moisture accretion.

Soil moisture samples were taken at replication 3 on August 11, 1959 to see if the difference in water storage remained. Approximately 4.00 inches of precipitation occurred between the April and August sampling periods. The check plot had a thin cover of herbaceous vegetation at the time of the August sampling. Only a difference of about 0.30 inch of soil moisture separated the check plot from an average of the Medium and Heavy density plots on August 11. Soil cracking was observed to begin in early May, and it is quite possible that evaporation alone could account for the disappearance of soil moisture at depths of 30 inches.

SUMMARY AND CONCLUSIONS

The demand for increased water supplies for the rapidly expanding population centers in the arid valleys of Arizona is intense. One possibility for increasing water supplies involves management of the upland watersheds which contribute surface water to the arid valley reservoirs. Federal money was appropriated for both a pilot project and a research program on these upland watersheds.

This study is a part of the research program, conducted by the Rocky Mountain Forest and Range Experiment Station of the U.S. Forest Service. It is designed to obtain basic information relating to watershed management, with particular reference to the Beaver Creek Watershed Project. The study is exploratory in nature, since so little was known of the hydrology of the area. Results will furnish a portion of the information needed to define the area problems and to orient the direction of continuing research. Objectives were to make a preliminary determination of the disposition of the precipitation that falls in Utah juniper stands growing within a fairly average range of sites on the Beaver Creek Drainage, and to explore some of the factors which control the disposition process. Secondary objectives were to provide complementary information regarding soil properties and root characteristics of Utah juniper.

General.

The study area lies on the Mogollon Rim at an elevation of about 5,500 feet. Topography is rolling to hilly with occasional steep-walled



canyons cut by ephemeral streams. The underlying rock formations are composed of heterogenous volcanics, ranging from red, porous cinders to bluish, dense basalt.

Nine study plots were located adjacent to three watersheds, 250, 310, and 330 acres in size, now being calibrated in the Utah juniper type on the Beaver Creek Watershed. Data were collected for one year beginning April 24, 1958. A check plot was also established and data collected beginning June 20, 1958.

The plots and small watersheds are enclosed by a network of precipitation gages established in 1957. Records from these gages show that most precipitation occurs as high intensity, short duration summer storms and low intensity winter storms of one to three days. These records agree with general findings throughout Northern Arizona. Hygrothermograph records within the same network show an annual average temperature of about 55 degrees, with extremes of 6 and 104 degrees. Relative humidities of 5 to 15 percent during the usually dry spring and fall are not uncommon. The storm distribution during the period of study was very uneven.

Vegetation on the plots is preponderantly Utah juniper (Juniperus Utahensis (Engelm.) Lemm.), with occasional clumps of turbinella oak (Quercus turbinella Greene) and individual pinon pines (Pinus edulis Engelm.). Ground vegetation is sparse; rock, bare soil and juniper leaf litter making up about 35, 50 and 15 percent of the surface cover respectively. Slopes varied from 2 to 7 percent.

Soils.

The soils on all plots were identified as belonging to the Springerville series. The series description is given for an eastern part of Arizona where the average soil depth ranges from 30 to 50 inches. Soils on the experimental plots averaged slightly over 30 inches, but a range of 6 to 94 inches was encountered from individual soil moisture samples. The soils on the plots contain about 65 percent montmorillonitic-type clay; wilting point is about 19 percent and field capacity about 37 percent soil moisture; bulk density averages about 1.33 and total available water-holding capacity is about 2.50 inches per foot of soil; average pH is about 7.5 and color of the subsoil is reddish brown (5YR 4/3). These soils are very hard when dry and very plastic and sticky when moist.

The montmorillonitic-type clay, with its 2:1 lattice structure, produces a pronounced swelling and shrinking of the soil body with changes in soil moisture. The periodic swelling and shrinking leads to a self-swallowing action, thought to be responsible for the concentration of rock in the upper foot of soil and on the surface. The shrinking action can also produce large cracks which, beginning to show in late spring, can occur to the depth of the soil body. These cracks appear to be responsible for greatly increasing the infiltration capacity of the soils.

Roots.

A study of the rooting habits of Utah juniper indicates that the great bulk of roots is located within the upper three feet of soil.

Some roots, however, are known to occur at depths of at least fifteen feet. Large roots are rather uniformly distributed, while a concentration of fine roots occurs in the upper 18 inches of soil.

Stand Density.

In order to relate the disposition of precipitation to stand density, some measure of stand density was required. The stands on the nine plots were measured by eight different methods, relating primarily to crown volume and number of trees. A strong correlation was shown to exist between percent crown density as measured by a spherical densiometer and all other methods. This strong correlation eliminated the need to test all stand density measures against the factors in the disposition process.

Surface Runoff, Depression Storage, Subsurface Flow, and Percolation.

Depression storage, subsurface flow and percolation were found to be negligible factors. Due to the limited data, an intensive analysis of the surface runoff component was not warranted. The plot data do show that a disproportionately large amount of surface water movement occurred on plots having shallow soils, about 6 inches deep, fairly steep slopes, 5 to 6 percent, and scanty vegetation. Other data suggest that surface water movement seldom occurs where juniper leaf litter covers the ground and that it increases with an increase in percent rock cover on the surface.

Streamflow records from the three, small watersheds averaged about 0.22 inch surface runoff for the period of study. During a three-week period over 5.50 inches of precipitation occurred, including two fairly intense storms of about 1.00 and 3.50 inches. This period produced the 0.22 inch surface runoff, indicating that the soil cracks, apparent at

the time, were responsible for increasing the infiltration capacity on the seemingly impermeable soils.

Stemflow.

Stemflow contributes a relatively small amount of water to the soil, about 2 percent of total precipitation. It begins to occur when rain storms exceed 0.25 to 0.30 inch. The shaggy bark of Utah juniper is probably responsible for these comparatively high values. No stemflow was recorded after snow storms, even those exceeding 1.00 inch water equivalent. Most likely the increased opportunity for evaporation and the fact that some snow is simply blown off the trees accounts for this phenomenon.

Interception.

During the course of 34 storms, over 1,200 randomized measurements were taken of net precipitation. Results showed that interception accounted for an average of 15 percent of gross precipitation. This amount varied from 2 to 24 percent, depending on stand density.

Of the eight stand density measures used to describe the plots, percent crown density using the spherical densiometer showed the best relationship with total percent interception. For practical field purposes, however, a simple count of the number of trees higher than 10 feet appears to be as satisfactory for predicting interception.

Regression analysis showed that the per storm relationship between gross and net precipitation was linear. Covariance analysis of these regressions showed significant differences in net precipitation between averages of the Light, Medium and Heavy density plots.

A more intensive analysis showed that net precipitation per storm was both a direct, linear function of gross precipitation and an inverse function of the square of stand density as measured by the spherical densiometer. Gross precipitation was a much more important factor in predicting net precipitation.

Soil Moisture and Stand Density.

The inches of water stored in the soil was determined by monthly periods on the nine plots from April, 1958 to April, 1959 and on the check plot from June, 1958 to April, 1959. Differences in inches of soil water storage were computed between months by 6-inch intervals for each plot.

Several attempts were made to relate soil moisture use to stand density. Since differences in soil moisture use would be masked if soil moisture was near wilting point, the shape of the depletion curve was studied. Soil moisture at each sampling date was expressed as percent available water of total available water-holding capacity. It was shown that from about 65 percent down to 5 percent the rate of available water withdrawal was nearly constant and was nearly equal for each 6-inch depth interval down to 30 inches.

Two drying periods, when soil moisture was available above 5 percent and other conditions were favorable, were selected for their ability to show differences in soil moisture use between different stand densities. These periods covered a total of 106 days. Average inches of soil moisture withdrawn daily from 30 inches of soil showed no real difference between Medium and Heavy density plots during either

period. A similar comparison was made for the Light, Medium and Heavy density plots at replication 3 where all other site factors were nearly identical. No differences in soil moisture use in 24 inches of soil were noted during either period.

Evapotranspiration of Soil Moisture.

Evapotranspiration of soil moisture was computed for each plot from the "water balance" formula. Yearly values ranged from 12.74 to 18.17 inches. To explain the differences between plots, the effects of stand density, net precipitation and soil depth were studied. These factors were mutually interrelated, but when their independent effects on evapotranspiration of soil moisture were identified, it was found that differences in stand density had little effect, while differences in soil depth were more important than differences in net precipitation.

Soil depth was important because it reflected the comparatively large differences in net change in soil moisture storage and because it indirectly influenced net precipitation through its influence on stand density. Stand density was not important because prolonged periods of little available water and cold weather restricted its full expression.

The Check Plot.

At the end of a 10-month period the check plot contained about 3.40 more inches of soil moisture in 30 inches of soil than the Medium and Heavy density plots at replication 3. By August, 1959, however, this difference had almost completely disappeared. About 4 inches of rain had fallen from April to August, 1959.

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Appendix 1. Methods of Determining Rates of Evapotranspiration

Vapor Flow Methods.

A. The Dalton Equation.

The first method of determining evapotranspiration by vapor flow methods makes use of the basic formula:

$$E = a(1 + bu) (e_s - e_a)$$

E is the rate of evaporation.

a and b are empirical constants.

u is windspeed at a given height.

e_s and e_a are vapor pressures at the surface and in the bulk air respectively.

According to McIlroy (1957),

"Almost all of the work done in this connection has been on evaporation from water surfaces. This permits e_s to be taken as e_s , the saturated vapor pressure at the surface temperature."

He then discusses Rohwer's studies, where the constant for a becomes 0.4; the constant for b becomes 0.27; u is surface wind in mph; and e_s and e_a are expressed in mm/day.

Again quoting McIlroy,

"Visentini [1936] and others have preferred to use in place of the ground-to-air vapor pressure drop the more easily measured quantity $e_a - e_a$, or saturation deficit (s.d.). Here e_a is the saturated vapor pressure at the bulk air dry bulb temperature T_a . This is based on the erroneous belief that the evaporative power of the air is dependent on its 'absolute' dryness as expressed by s.d., rather than its 'relative' dryness as indicated by the vapor pressure difference between ground and air. Although it has no physical justification the use of s.d. as an index of evaporation has apparently given moderately successful results in certain applications,"

Van der Bijl (1956-1957) then reviews the work of Albrecht, Haude, Kalweit, Ivanov, Skvortsov and Poliakov, all of whom apply some modification of the saturation deficit approach to geographical areas with varying degrees of success.

B. The Aerodynamic Approach.

The second method of determining evapotranspiration by vapor flow methods is called the "aerodynamic approach." For a more complete theoretical background, the reader is referred to Sutton (1953) and Haltiner, et al. (1957), since only the main outlines will be presented here. The fundamental problem involves a determination of the turbulent transfer of water vapor at a small distance above the ground. Dalton's empirical constant, a , is replaced by an "eddy transfer coefficient" and the ground-to-air vapor pressure drop by the specific humidity gradient. To understand why this method is in better accord with physical principles of evapotranspiration, consider the following description of a field situation by Sutton:

"To fix ideas, consider conditions near level ground, either bare or covered with short grass, in the afternoon and evening of a clear day in early summer or in the fall, in the circumstances in which the synoptic chart shows only small horizontal gradients of pressure. When the sun is high in the heavens, the temperature of the surface rises considerably above that of the air immediately adjacent to it and the wind is highly turbulent. As the sun sets, the temperature of the ground falls rapidly below that of the air, with the result that the layers of the atmosphere immediately in contact with the ground are chilled and become denser than those above. The maintenance of the turbulent state implies that masses of air are being removed continually in the vertical, so that if the fall of density with height is very pronounced, considerable work has to be done in lifting the denser masses against the gravitational field, at the expense of energy of the mean motion. The inevitable result is that, in such circumstances, the

turbulent motion becomes less pronounced and may even die away completely. This, in turn, means that the supply of momentum from the free stream to replace that absorbed by the friction of the ground is reduced because of the loss of mixing, and the flow, as a whole, tends to settle down to slow motion in parallel layers. Provided that the sky remains clear and that there are no large horizontal pressure gradients, this state of affairs will generally continue until dawn, when the incoming radiation raises the temperature of the ground, and ultimately that of the lowest air layers. The position is now reversed, for the less dense air is below, and any tendency to vertical motion is enhanced by the prevailing density distribution. Soon after dawn the near-laminar flow gives place to turbulent motion, which continues throughout the day."

The specific humidity gradient can be measured directly by suitable hygrometers. The difficulty comes in determining the "eddy transfer coefficient." To get the meaning of this term and the theory of measurement, we again quote Sutton:

"....much of the early work, and especially that on atmospheric turbulence, was based on a 'kinetic-theory' model, in which wandering masses of fluid, called eddies, were supposed to behave like molecules, . . .

"A first natural step toward a theory of turbulence is to adopt the fundamental ideas of the kinetic theory of gases by expressing the transfer of momentum, or any suitable, conservative entity, by means of virtual coefficients of viscosity, conductivity, and diffusivity, defined in much the same way as their molecular counterparts."

An expression of turbulent flux, independent of any theory of the structure of eddy motion is shown to be:

$$\text{"Mean flux} = k \frac{d\bar{E}}{dz} - p\overline{E'w'} \quad (3.11)$$

k is the appropriate molecular coefficient (viscosity, conductivity, diffusivity).

E is the amount per unit mass of fluid of any transferrable conservative entity.

z is height, or direction perpendicular to the xy plane.

$pE'w'$ is the amount of E transported in unit time through unit cross section of a plane parallel to $z = 0$.

"Thus the mean flux across a plane perpendicular to the z direction depends chiefly upon the existence of a correlation between the fluctuations in velocity and in the entity being transferred. If momentum is being transferred, $E = u$, $k = \mu$, and thus

$$\text{Mean flux} = \mu \frac{d\bar{u}}{dz} - \overline{pu'w'}$$

in which the second term will be recognized as the appropriate Reynolds stress, the mean flux of momentum being the frictional force per unit area, or shearing stress. Matter in suspension, such as water vapor, smoke or dust, implies that E be expressed as grams of matter per gram of air - thus for the diffusion of water vapor E must be the specific humidity, or the ratio of absolute humidity to the density of the (moist) air, so that pE is the absolute humidity, or concentration of water vapor (mass per unit volume).

"The fundamental problem in the analysis of turbulent mixing is to express (3.11) in terms of the mean entity E and its derivatives. The exchange-coefficient hypothesis is that the term $-\overline{pE'w'}$ can be expressed as the product of a virtual coefficient of mixing and the gradient of the mean entity $d\bar{E}/dz$."

For the conservative property, momentum, the analogy between molecular and eddy motion was extended by Prandtl (1934), who developed a "mixing length" term which is analogous to the mean free path of molecular motion, and by von Karman (1953), who was able to express the Reynolds stress in terms of molecular motion. However, Sutton (1953) suggests that the "mixing length" term fails to account for large eddies. Taylor's (1932) "vorticity-transfer" theory is discussed along with statistical theories and a "similarity theory" of Kolmogoroff's (1941). These theories are an improvement on the "mixing length" theory, but none of them are adequate as yet. Halstead (1954) introduces correction terms in the transfer of momentum for effects of surface roughness and variations in temperature with height.

When the "eddy transfer coefficients" are expressed in terms of conductivity or diffusivity there is usually an implicit assumption that they may be equated with each other and with momentum. Pasquill (1949) used field measurements to test the aerodynamic theory. He points to the work of Taylor (1931) and Priestly and Swinbank (1947) in relation to the buoyancy effect, and demonstrates that the aerodynamic theory holds only under neutral conditions, or when the lapse rate, or rate of temperature fall with height, is small. It is shown that, in the absence of thermal stratification, the relationship between the fluxes of momentum, heat and water vapor is valid. Under non-neutral conditions the relationship is not valid, but may be minimized by taking measurements close to the ground. Berger-Landefeldt (1956) summarizes the limitations of the aerodynamic approach. Besides those already mentioned, he stresses that the accuracy requirements for the instruments are prohibitive using Halstead's assumption of a logarithmic wind profile; that neutral conditions are comparatively infrequent; and that microclimatic influences, rather than instrumentation difficulties, may be responsible for the general failure of the method.

Extensive field trials were conducted during the Great Plains Turbulence Field Program, sponsored jointly by ten universities and five government scientific organizations. The data collected permitted a comparison of the aerodynamic approach with the heat balance approach (discussed later). Site description, instrumentation and field data are presented in a final report (1957) of the A. & M. College of Texas, Dept. of Oceanography and Meteorology. The Johns Hopkins Laboratory of

Climatology (1954) also issued a final report on earlier work, which provides an excellent discussion of the instrumentation problem. Van der Bijl (1957-1958), using the field data, made comparisons in evapotranspiration rates between the methods of Halstead and Suomi (aerodynamic and heat energy approaches, respectively). The field data also permitted him to compare evapotranspiration rates using the formulas of Thornthwaite and Lettau. His conclusions are:

"The relationship between evaporation as a dependent variable and meteorological parameters as independent variables for periods less than a few hours cannot yet be determined. For longer periods the agreement between computed and actual evaporation values improves, but the same can be said for the values computed with the help of simple formulas (Thornthwaite's. Author's note.)."

C. Direct Eddy Flux Determination.

The third method of determining evapotranspiration by vapor flow methods involves a direct determination of the vertical eddy flux of water vapor, which is the component indirectly achieved by the aerodynamic approach. Since McIlroy (1957) was instrumental in the development of this method, we can do no better than quote him:

"At any point in the atmosphere turbulent air movement will normally be present, giving rise to a fluctuating vertical component of windspeed. In the presence of a vertical gradient of humidity these fluctuations will be associated with simultaneous fluctuations in moisture content of the air. Rising air will tend, on the average, to be moister or drier than descending air, according to the sign of the gradient. This will give rise to a net transfer of water vapor along the gradient.

"The mean rate of this transfer, per unit time and per unit area, is known as the vertical eddy flux of water vapor. Letting a bar over a quantity denotes its mean value with respect to time, and a dash the difference between an instantaneous value of a quantity and its mean value, the eddy flux is given by

$$E^X = \overline{(pW)'q'}$$

where p , W and q are simultaneous values of air density, vertical windspeed and specific humidity at the measuring point. Hence $(pW)'$ represents an instantaneous fluctuation in the rate of upward air flow at the point, and q' an associated fluctuation in moisture content.

"Records of pW and q taken at a point near the ground, ... will permit the direct evaluation of E^X , which is of course the quantity sought indirectly by the aerodynamic approach.

"It is obviously impossible to measure instantaneous values of pW and q , but with sufficiently rapid response instruments only comparatively high frequency fluctuations are missed, and these make little contribution to the total transfer.

"The actual rapidity of response required for satisfactory flux measurement depends on the pattern and scale of the turbulence. In general the requirement decreases with height above ground and increases with windspeed. It also varies with the roughness of the surface and with certain weather factors.

"At heights of a meter or more a response time of about a fifth of a second appears to be adequate under most circumstances. This means in effect neglecting fluctuations much faster than a second in period.

"Such a rapid response cannot be obtained with standard meteorological equipment but is well within the limits of performance of fine sensing elements. However, rather elaborate recording or computing systems are necessary. Apart from this and the degree of sampling variation likely to be encountered, the method is completely independent of the nature of the surface above which the measurements are made. Much further work is required before regular field use of this technique will be possible. However, there is no doubt that it is even now the best available for accuracy and general applicability."

Surface Energy Balance.

This method makes use of the formula

R equals G plus H plus LE , where

R is net radiation

G is heat flux into the ground

H is sensible heat flux

LE is latent heat flux of evaporation

A more complicated form is given by Tanner (1957) and Tanner and Suomi (1957), in which vertical and horizontal flow are separated, and changes in both sensible and latent heat stored in the "volume" (air, crop and water vapor) are considered. They point to the work of Rider and Robinson showing that if neglected the storage term will only introduce an error of about 1 percent during clear days when E_t is high, and about 10 percent during sunrise, sunset and nighttime, when E_t is low. Ignoring the horizontal flow factor (divergence) may produce errors as large as 40 percent, however. When measurements are taken near the ground or crop surface, the horizontal divergence is greatly minimized. The heat flux into the ground is measured directly by thermometers near the surface and heat plates deeper in the soil. Net radiation is measured directly by the "economical net radiometer" developed by Suomi (1956). Van der Bijl (1957-1958) makes a comparison of several types of net radiometers, concluding that Suomi's model could be improved by "providing the radiometer with sensors of larger heat capacity" to obtain more reliable results for one hour periods. Other models are compared, and he recommends the use of standardized testing surfaces. The chief difficulty encountered in the energy balance approach lies in separating the latent and sensible heat terms. This separation is usually performed according to the Bowen Ratio. This ratio was determined for conditions of laminar flow, where the

coefficients of heat and water vapor transfer were shown to be equal.

As Tanner (1957) comments, however,

"There is some controversy regarding both the equality of K_h and K_w (turbulent transfer coefficients of heat and water vapor, respectively) and the constancy of K_h/K_w as atmospheric stability changes (the "bouyancy effect")."

He further states:

"The main advantage of the energy balance--Bowen ratio method as compared to aerodynamic methods, which require a product of the wind and vapor pressure gradients, is the fact that the measurement of net radiation and soil heat flux is made at the surface and places reasonable limits on the magnitude of the sensible and latent heat flux. The aerodynamic method refers all the measurements to a region in the atmosphere. Both methods include assumptions on the eddy coefficients of transfer but the error in the aerodynamic method is proportional to the errors arising from an incorrect assumption concerning the eddy coefficients whereas the energy balance method is less sensitive...."

Combined Surface Energy Balance and Dalton Equation.

This method is associated with the names of Penman (1949) and Ferguson (1952) who independently arrived at the conclusion that, where a relationship could be established between the temperature and vapor pressure at a surface, then the energy balance equation could be combined with the Dalton type equation to eliminate both of these variables. Such a relationship is rather readily established for a water surface. According to Penman (1949):

".... the chief justification of the great attention given to evaporation from open water is found in the opportunity it presents of providing a reproducible surface of known properties. Because of this, it is convenient to approach the problems of the dependence of evaporation from bare and cropped soil on weather conditions through a study of evaporation from open water, seeking an absolute relation between weather elements and open water evaporation, and comparative relations between losses from the soil and losses from open water exposed to the same weather.

Evaporation from an open water surface is approximated by a combining of the energy balance and Dalton type equations."

For the mathematical treatment and assumptions used, the reader is referred to Penman's original paper (1949). The final expression becomes

$$E = \frac{(H\Delta + E_a\gamma)}{(\Delta + \gamma)}$$

E is evaporation in unit time.

H is net radiant energy available at the surface.

Δ is de_a/dT_a , where e_a and T_a are sat. vapor pressure and temperature of the air, respectively.

E_a is value of $E(o)$ obtained by putting $e_s = e_a$.

γ is constant of wet and dry bulb hygrometer equation.

Empirical coefficients, based on lysimeter tests, are then obtained for the relationship between evaporation from open water (E_o), bare soil (E_b) and crop cover (E_t). They are shown below:

$$\frac{E(b)}{E(o)} = .90$$

$$\frac{E(t)}{E(o)} = .75$$

This method has met with the same sort of limited success as

Thornthwaite's method because of the large empirical content and simplifying assumptions.

Appendix 2. Techniques Used to Determine Soil Properties

1. Soil color was determined from Munsell color charts after wetting the soil to a 1 : 1, soil to water, ratio.
2. Soil pH was determined with both a Beckman pH Meter and Fisher titrimeter.
3. Soil texture was determined by the Bouyoucos method.
4. Upper plastic limits were determined by the Yoder method.
5. Bulk density was obtained with the sampler and procedure proposed by Carey.
6. Laboratory methods of determining soil moisture at 20- and 60-cm tension are described by Hoover, Olson and Metz.
7. July soil moisture determinations, preceded by 70 consecutive rainless days, were used for an approximation of permanent wilting point. Wilting point was determined at 15 atmos. using a pressure membrane, but consistently yielded results 2 to 5 percent higher than the July readings.

Appendix 3. Monthly soil moisture (percent by weight) value for Light and Check plots.

Depth (inches)	1958							1959						
	4	5	6	7	8	9	10	11	12	1	2	3	4	
Plot 1-L														
0-6	22.7	10.4	4.0	3.3	15.7	19.6	18.5	24.8	16.5	15.1	21.3	11.3	9.6	
Plot 2-L														
0-6	21.1	7.5	4.7	3.8	13.1	24.2	19.1	24.4	16.0	15.6	28.3	14.2	12.2	
Plot 3-L														
0-6	24.2	23.2	14.2	10.1	11.5	27.9	23.8	28.3	21.6	21.7	28.0	21.6	19.2	
6-12	27.7	23.9	18.8	14.6	14.4	26.2	27.7	24.5	19.4	21.6	25.9	26.2	21.1	
12-18	28.9	24.5	20.8	16.2	17.0	26.8	25.6	20.8	21.4	20.5	20.6	23.9	21.1	
18-24	29.1	25.8	19.1	19.7	19.4	25.4	25.7	17.9	21.8	20.8	20.8	26.3	20.7	
Plot 3 Ck.														
0-6			9.0	7.4	12.1	26.0	22.7	29.4	22.7	25.8	30.1	23.1	24.3	
12		15.8	14.9	14.4	14.4	23.9	25.1	27.8	28.3	27.7	28.5	26.9	24.9	
18		16.8	16.2	15.5	15.5	21.7	20.6	27.0	26.1	24.2	27.9	24.9	26.2	
24		16.6	16.9	16.3	16.3	22.1	22.1	24.2	22.0	22.2	25.5	21.8	26.9	
30		16.8	15.3	16.8	16.8	20.5	22.6	22.2	21.9	20.0	20.1	22.7	26.3	

Appendix 3. Monthly soil moisture (percent by weight) value for Medium plots.

Depth (inches)	1958							1959						
	4	5	6	7	8	9	10	11	12	1	2	3	4	
Plot 1-M														
0-6	30.1	33.5	13.1	16.1	18.2	29.8	28.1	31.0	23.8	22.7	30.6	19.6	20.4	
12	33.4	26.4	22.5	22.0	21.2	27.2	30.2	25.9	26.1	24.3	29.8	25.0	22.8	
18	32.5	28.1	23.9	22.4	20.5	24.2	26.9	23.4	26.2	23.5	23.7	25.0	22.6	
24	32.0	30.2	24.7	22.1	20.2	21.9	23.7	22.8	24.9	23.6	23.7	24.5	22.3	
30	30.9	29.8	26.1	21.9	19.9	22.8	22.8	22.6	23.7	25.7	22.4	23.9	22.3	
36	31.4	28.8	25.2	23.1	20.0	23.7	22.8	22.1	23.9	26.0	22.9	24.6	33.0	
42	31.4	28.4	25.8	23.2	20.7	21.9	23.7	23.5	25.1		25.3	24.5	23.5	
48	29.8	25.8	26.5	23.6	23.0	22.4	25.0	25.4	21.1		25.3	26.5	23.8	
Plot 2-M														
0-6	25.6	21.5	13.0	14.6	13.9	32.5	29.7	31.9	28.4	26.4	30.5	21.6	21.0	
12	34.5	25.2	19.4	17.5	17.6	30.7	28.3	26.3	29.6	25.6	27.9	26.3	22.6	
18	31.7	24.0	20.7	17.8	17.9	26.0	27.7	22.8	29.2	23.0	26.5	25.2	22.2	
24	31.8	24.1	21.1	18.1	19.1	24.0	27.5	25.1	28.0	23.2	24.9	23.6	22.3	
30	32.3	26.2	20.6	18.5	19.4	24.5	27.1	24.6	27.5	22.8	25.0	24.0	21.9	
36	33.5	24.6	22.7	19.2	20.3	25.0	26.5	25.3	25.1		24.6	27.2	22.0	
Plot 3-M														
0-6	26.3	18.7	12.5	12.1	11.9	24.1	21.8	26.3	20.5	19.4	28.1	15.1	20.1	
12	27.7	20.4	18.1	16.8	16.2	23.8	24.2	21.5	20.6	19.4	24.9	19.4	20.2	
18	28.1	24.2	19.5	17.3	17.5	20.5	22.3	20.9	20.5	19.8	20.6	19.2	20.3	
24	27.8	24.8	19.8	17.6	16.9	19.5	19.6	19.8	20.5	19.2	20.2	19.8	20.1	
30	26.9	22.4	19.3	17.8	17.6	19.0	19.5	19.8	20.0	19.7	19.6	19.5	20.4	
36	26.3	19.4	19.6	18.0	17.8	18.7	19.0	19.0	19.6	18.9	21.1	19.2	20.2	
42	21.3	19.4	19.4	18.4	17.6	17.7	19.5	18.9	19.4	19.1	20.2	19.0	20.0	
48	21.3	19.5	19.4	18.1	18.4	17.7		19.4		19.1	19.8	18.8	19.5	

Appendix 3. Monthly soil moisture (percent by weight) value for Heavy plots.

Depth (inches)	1958							1959						
	4	5	6	7	8	9	10	11	12	1	2	3	4	
Plot 1-H														
0-6	31.6	36.3	15.6	13.9	20.3	25.4	25.4	30.2	23.5	26.0	33.5	18.3	22.4	
12	34.4	26.8	23.6	22.0	20.5	26.2	29.0	25.9	25.7	25.1	26.8	22.9	23.7	
18	29.6	27.4	24.1	22.2	23.2	22.4	25.1	24.8	23.2	23.8	24.7	22.8	22.8	
24	31.0	27.3	24.0	21.8	23.0	20.8	24.0	23.9	23.4	23.2	24.7	23.2	21.8	
30	30.3	26.9	23.8	21.9	22.4	22.2	23.0	24.4	22.0	22.8	24.2	23.4	22.4	
36	30.2	25.5	23.2	22.4	22.6	22.9	23.3	24.2	22.5	23.2	24.2	23.7	21.0	
42	30	24.3	23.4	22.8	22.2	23.5	24.1	24.1	22.7	23.2	25.2	25.1	23.3	
48	30	24.8	25.8	23.2	22.8	23.2	23.8	24.2	23.4	24.4	25.2	24.3	24.3	
Plot 2-H														
0-6	31.3	22.5	10.4	10.5	20.5	34.7	26.0	31.4	26.0	24.9	28.9	17.7	22.2	
12	31.5	25.4	18.8	19.1	20.3	32.3	25.8	27.5	25.3	23.9	25.3	23.1	22.8	
18	33.5	26.6	23.0	20.5	21.4	31.3	26.0	25.9	23.4	26.0	25.8	26.7	23.1	
24	32.0	24.8	23.4	20.2	21.1	29.0	25.8	26.5	24.6	25.7	25.9	25.5	23.7	
30	26.8	24.5	22.8	21.6	21.1	28.5	26.3	26.0	24.7	23.8	24.8	24.0		
36	23.7	22.5	22.3	21.2	21.7	26.1	20.7	24.6	24.6	23.0	23.9	23.8	23.4	
42	25.1		22.7		23.6	29.3		25.7	24.0	24.3	26.3	23.2		
Plot 3-H														
0-6	24.6	18.0	12.7	10.2	9.7	28.7	21.0	26.6	20.0	19.0	27.4	17.6	18.0	
12	27.5	21.4	18.5	15.7	15.4	22.8	20.3	24.0	20.2	19.6	20.8	19.3	18.1	
18	26.8	21.4	17.6	14.6	15.5	22.0	19.0	20.6	18.7	18.5	19.7	18.9	18.7	
24	26.8	21.4	17.3	16.2	15.8	21.1	17.8	19.3	18.7	18.7	19.4	18.4	19.1	
30	26.6	21.6	18.2	16.0	15.4	21.0		19.6	19.2	19.2	19.4	18.4	18.2	

Appendix 3a. Procedure used to correct percent moisture for rock.

Dry screening was impossible, since some rock was crushed by the pestle as readily as the oven-dry clay. About 10 samples per 6-inch depth interval per plot were collected after oven-drying, weighed, and reduced to a slurry. The slurry was then passed through a 2 mm screen, the stones separated and weighed.

Percent stone of oven-dry soil weight was computed for each 6-inch depth interval for each plot. These values were then plotted on graph paper and curves drawn. The curved values are shown on the following page.

Curved values were then used to correct P_w for all sampling dates. A check was made by repeating the above procedure for samples taken on March 3, 1959. Agreement between curved and actual values was good; the maximum deviation would change inches of water in a 6-inch depth interval by only 0.20 inch, while the maximum change for total soil depth did not exceed 0.40 inch. Most values were considerably smaller than this, and were not consistently in one direction.

Appendix 4. Bulk density and related soil properties.

Plot no.	Depth in.	Bulk Density	Water Held at Saturation		Water Held at 60-cm Tension		Water Held Between Sat. & 60-cm		Total Porosity = 100%	
			Pw	Pv	Pw	Pv	Pw	Pv	Noncapillary Porosity	Capillary Porosity
1-H	0-3	1.12	50.5	56.5	48.4	54.1	2.1	2.4	4.2	95.8
		.88	64.9	56.9	53.6	47.1	11.3	9.8	17.2	82.8
		.93	64.4	59.7	55.1	51.1	9.3	9.5	14.4	85.6
		1.15	48.0	55.3	45.6	52.4	2.4	2.9	5.2	94.8
		1.17	46.0	53.8	42.8	50.1	3.2	3.7	6.9	93.1
	3-6	1.13	51.4	58.1	43.5	49.2	7.9	8.9	15.3	84.7
		1.14	46.5	53.2	43.9	50.2	2.6	3.0	5.6	94.4
	9-12	1.24	40.8	50.4	38.8	48.0	2.0	2.4	4.8	95.2
		1.29	42.0	54.2	37.2	48.1	4.7	6.1	11.3	88.7
		1.29	39.2	50.6	37.2	48.1	1.9	2.5	5.0	95.0
	15-18	1.26	41.6	52.6	40.6	51.4	1.0	1.2	2.3	97.7
		1.25	41.1	51.6	39.5	49.5	1.6	2.0	4.1	95.9
		1.32	38.1	50.3	36.5	48.2	1.5	2.0	4.2	95.8
		1.35	36.3	49.1	35.1	47.5	1.2	1.6	3.3	96.7
	21-24	1.31	37.1	48.6	35.2	46.1	1.9	2.4	5.2	94.8
		1.25	43.5	54.3	42.5	53.0	1.0	1.2	2.4	97.6
	27-30	1.35	36.2	48.8	35.2	47.5	.9	1.2	2.7	97.3
		1.32	38.1	50.3	36.5	48.3	1.5	2.0	4.0	96.0
	33-36	1.35	38.3	51.8	37.4	50.6	.9	1.2	2.3	97.7
	45-48	1.31	39.3	51.5	38.1	50.0	1.2	1.6	2.9	97.1
		1.29	43.4	56.2	38.4	49.6	5.0	6.5	11.8	88.2
	51-54	1.30	39.6	51.5	38.3	49.8	1.2	1.6	3.3	96.7
		1.30	40.4	52.5	38.8	50.5	1.6	2.0	3.8	96.2
	57-60	1.26	46.0	57.9	40.9	51.5	5.1	6.4	11.1	88.9
	63-66	1.29	41.8	53.8	38.4	49.4	3.4	4.4	8.2	91.8

Appendix 4. Bulk density and related soil properties (continued).

Plot no.	Depth in.	Bulk Density	Water Held at Saturation		Water Held at 60-cm Tension		Water Held Between Sat. & 60-cm		Total Porosity = 100%	
			Pw	Pv	Pw	Pv	Pw	Pv	Noncapillary Porosity	Capillary Porosity
2-H	0-3	1.20	48.6	58.6	41.5	50.0	6.5	7.8	14.7	85.3
		1.08	60.3	64.9	49.1	52.8	11.2	12.1	18.6	81.4
		1.05	59.3	62.4	45.7	48.2	13.6	14.3	22.8	77.2
	9-12	1.33	38.3	50.8	35.8	47.5	2.5	3.3	6.5	93.5
	15-18	1.34	37.9	50.8	35.2	47.1	2.8	3.7	7.3	92.7
		1.34	37.8	50.8	36.2	48.8	1.5	2.0	3.9	96.1
	21-24	1.36	38.2	52.0	35.8	48.8	2.4	3.2	6.2	93.8
		1.35	37.6	50.6	35.4	47.8	2.1	2.8	5.5	94.5
	27-30	1.35	36.6	49.6	34.8	47.2	1.8	2.4	4.8	95.2
		1.39	36.9	51.2	34.5	48.0	2.4	3.3	6.2	93.8
2-M	33-36	1.39	37.3	52.0	34.7	48.4	2.6	3.6	6.9	93.1
	39-42	1.37	37.6	51.6	35.0	48.0	2.6	3.6	7.0	93.0
	45-48	1.41	38.9	54.9	35.7	50.4	3.1	4.4	8.2	91.8
	0-3	1.22	43.7	53.5	40.0	49.0	3.7	4.6	8.4	91.6
		1.16	48.9	56.5	40.5	46.8	8.4	9.7	17.2	82.8
		1.05	59.4	62.6	53.1	56.0	6.3	6.6	10.6	89.4
	3-6	1.22	40.7	49.8	38.4	47.0	2.3	2.8	5.6	94.4
		1.28	40.0	51.3	39.0	50.0	1.0	1.3	2.5	97.5
	9-12	1.24	43.5	53.9	38.8	48.1	4.7	5.8	10.8	89.2
	15-18	1.25	42.8	53.5	38.7	48.3	4.2	5.2	9.7	90.3
		1.32	37.0	48.8	35.1	46.3	1.9	2.4	5.1	94.9
	21-24	1.33	36.6	48.8	35.0	46.7	1.6	2.1	4.3	95.7
		1.40	34.7	48.6	32.4	45.3	2.4	3.3	6.8	93.2
	27-30	1.34	35.8	48.0	34.2	45.9	1.5	2.0	4.4	93.6
		1.35	34.9	47.1	33.3	45.0	1.5	2.1	4.5	95.5
	33-36	1.41	31.4	44.4	30.6	43.1	.8	1.2	2.9	97.1
		1.40	33.9	47.6	31.3	43.9	2.6	3.6	7.8	92.2

Appendix 4. Bulk density and related soil properties (continued).

Plot no.	Depth in.	Bulk Density	Water Held at Saturation		Water Held at 60-cm Tension		Water Held Between Sat. & 60-cm		Total Porosity = 100%	
			Pw	Pv	Pw	Pv	Pw	Pv	Noncapillary Porosity	Capillary Porosity
3-Ck	0-3	1.22	42.5	51.8	39.1	47.8	3.3	4.1	7.7	92.3
		1.20	42.7	51.2	37.9	45.5	4.8	5.7	11.1	88.9
		1.14	48.9	55.9	44.0	50.2	5.0	5.7	10.2	89.8
	3-6	1.39	33.5	46.5	32.0	44.5	1.5	2.0	4.3	95.7
		1.29	37.3	48.1	35.0	45.3	2.2	2.9	5.8	94.2
		1.33	38.0	50.6	33.3	44.4	4.6	6.2	12.3	87.7
	9-12	1.41	32.2	45.5	30.2	42.7	2.0	2.8	6.2	93.8
	15-18	1.38	36.4	50.2	34.0	46.9	2.4	3.3	6.6	93.4
		1.36	36.9	50.4	33.9	46.3	3.0	4.1	8.1	91.9
	21-24	1.43	34.8	50.0	32.3	46.3	2.5	3.6	7.4	92.6
		1.44	34.4	49.4	32.1	46.2	2.2	3.2	6.5	93.5
	27-30	1.44	29.5	42.4	28.1	40.4	1.4	2.0	4.7	95.3
		1.45	32.8	47.7	31.4	45.6	1.4	2.1	4.4	95.6
	30-33	1.34	31.7	42.6	30.8	41.4	.9	1.2	2.8	97.2
		1.21	42.1	50.9	40.2	48.7	1.8	2.2	4.3	95.7

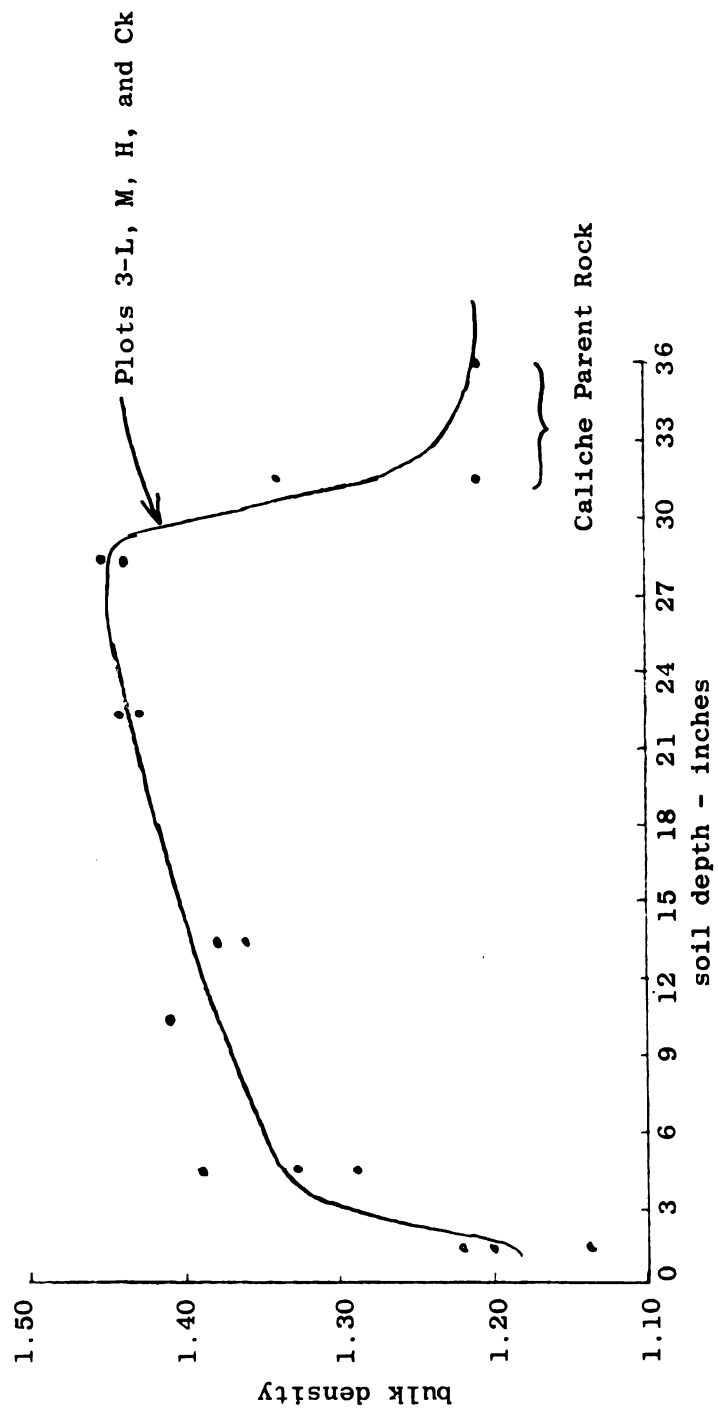


Appendix 4a. Procedure used to compute average bulk density for each plot.

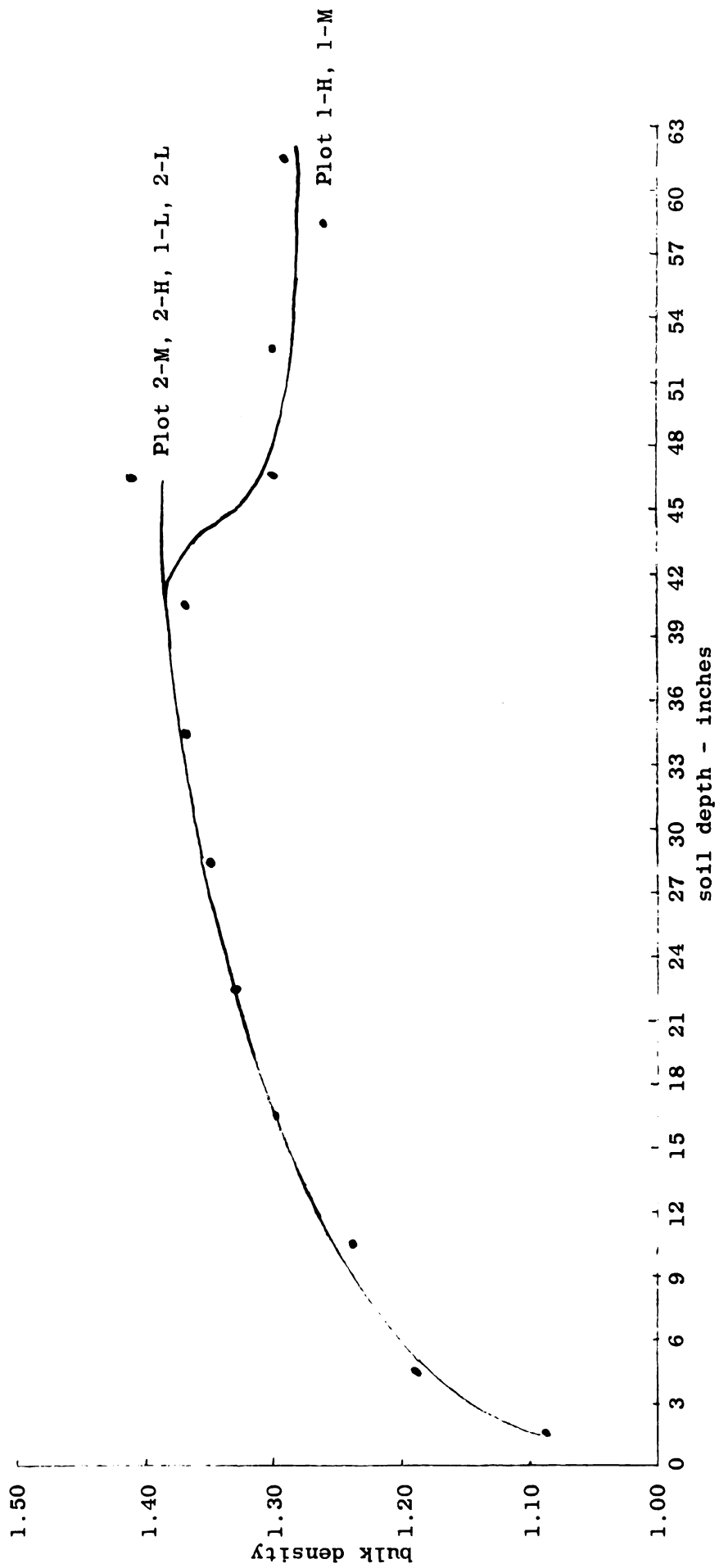
Bulk density samples were individually corrected for rock by the procedure outlined in Appendix 3a. A second oven-drying was not necessary in this case.

Bulk density values from plots 1-H, 2-H, and 2-M were combined because of similarities in soil properties and actual bulk density values. The check plot appeared to be distinct not only in terms of bulk density values, but also in texture, wilting point, soil moisture at 60-cm tension, and stoniness. This difference in soil properties other than bulk density was common to all the number 3 plots, and was not surprising since they are all grouped at one end of the study area.

Bulk density values were then plotted by averages for each 3-inch depth interval sampled. Curved values were then obtained at the midpoint of each 6-inch depth interval as shown and tabulated on the following three pages. Plots not sampled were assigned values from plots most resembling them in other soil properties.



Appendix 4a.



Appendix 4a.

Appendix 4a. Final curved values for bulk density.

Plot no.	Depth in.	Curved Bulk Density Value	
3-Check	0-6	1.26	
3-L	6-12	1.37	
	12-18	1.40	
	18-24	1.43	
	24-30	1.44	
	30-36	1.31	
3-M	0-6	1.20	Estimated (larger percent litter than 3-0)
	12	1.37	
	18	1.40	
	24	1.43	
	30	1.44	
	36	1.45)	
	42	1.45)	Estimated (no evidence of caliche from color, pH, texture, plastic limit tests)
	48	1.45)	
3-H	0-6	1.18	Estimated (larger percent litter than 3-M)
	12	1.37	
	18	1.40	
	24	1.43	
	30	1.44	
	36	1.31	
2-M	0-6	1.15	
2-H	12	1.23	
	18	1.28	
	24	1.32	
	30	1.35	
	36	1.37	
	42	1.38	
	48	1.39	

Appendix 4a. (continued).

Plot no.	Depth in.	Curved Volume Weight Value	
1-L	0-6	1.20	Estimated since less litter
1-M	0-6	1.15	
1-H	12	1.23	
	18	1.28	
	24	1.32	
	30	1.35	
	36	1.37	
	42	1.38	
	48	1.33	
	54	1.29	
	60	1.28	
	66	1.28	

Appendix 5. Average soil depth.

Plot	Mean	Range	Number Samples	10 Percent Confidence Interval	Standard Error
<u>no.</u>	<u>in.</u>	<u>in.</u>		<u>in.</u>	<u>in.</u>
*1-L	3.35	2-8	14	0.7	0.32
*2-L	3.41	2-7	14	.7	.32
3-L	21.1	12-30	45	1.1	.65
1-M	47.7	20-62	38	2.7	1.60
2-M	32.6	19-48	45	2.2	1.30
3-M	48.4	31-60	42	1.9	1.13
**1-H	48.0				
2-H	37.6	22-72	40	2.6	1.54
3-H	30.2	19-37	42	1.1	.68
3-Ck	31.6	24-44	35	1.3	.77

*Because of the difficulty of measuring the depth of soil intercalated with basalt, a depth of 6 inches was assigned to these plots.

**Because it was usually impossible to hit bedrock with an 8-foot tube, a depth of 4 feet was assigned to this plot. Soil moisture change below 4 feet never exceeded 1 to 2 percent between sampling dates, values well within the range of sampling error. Average soil moisture between 4 and 8 feet on April 22, 1958 and April 21, 1959, showed a difference of 0.7 percent.

Appendix 6. Inches of water stored in the soil by sampling date.

Depth: Apr. 24: Differ--: May 22: Differ--: June 20: Differ--: July 23: Differ--: Aug. 21: Differ--: Sept. 25: Differ--: Oct. 27										
: 4	: ences :	5	: ences :	6	: ences :	7	: ences :	8	: ences :	9 : ences : 10
<u>Plot 1-L</u>										
0-6	1.63	-0.88	0.75	-0.46	0.29	-0.05	0.24	0.89	1.13	0.28 1.41 -0.08 1.33
<u>Plot 2-L</u>										
0-6	1.52	-.98	.54	-.20	.34	-.07	.27	.67	.94	.80 1.74 -.36 1.38
<u>Plot 3-L</u>										
0-6	1.84	-.09	1.75	-.67	1.07	-.31	.76	.11	.87	1.24 2.11 -.31 1.80
12	2.28	-.32	1.96	-.41	1.55	-.35	1.20	-.02	1.18	.97 2.15 .13 2.28
18	2.43	-.37	2.06	-.31	1.75	-.39	1.36	.07	1.43	.82 2.25 -.10 2.15
21.1	1.29	-.14	1.15	-.28	.87	.02	.89	-.01	.88	.25 1.13 .01 1.14
Total		-.92		-1.67		-1.03		.15		3.28 -.27
<u>Plot 3-Ck</u>										
0-6			.68			-.12	.56	.35	.91	1.06 1.97 -.25 1.72
12			1.30			-.08	1.22	-.04	1.18	.78 1.96 .10 2.06
18			1.41			-.05	1.36	-.06	1.30	.52 1.82 -.09 1.73
24			1.42			.03	1.45	-.05	1.40	.50 1.90 .00 1.90
30			1.45			-.13	1.32	.13	1.45	.32 1.77 .18 1.95
Total						-.35		.33		3.18 -.06

Appendix 6. (continued).

Differ--:Dec. 1:Differ--:Dec. 30:Differ--:Jan. 29:Differ--:Mar. 3:Differ--:Mar. 30:Differ--:Apr. 21: Net												
ences : 11 : ences :		12 : ences :		1 : ences :		2 : ences :		3 : ences :		4 :		
<u>Plot 1-L</u>												
0.46	1.79	-0.60	1.19	-0.10	1.09	0.44	1.53	-0.72	1.81	-0.12	0.69	-0.94
<u>Plot 2-L</u>												
.38	1.76	-.61	1.15	-.03	1.12	.92	2.04	-1.02	1.02	-.14	.88	-.64
<u>Plot 3-L</u>												
.62	2.42	-.79	1.63	.01	1.64	.48	2.12	-.45	1.63	-.18	1.45	-.34
-.27	2.01	-.42	1.59	.18	1.77	.36	2.13	.02	2.15	-.42	1.73	-.55
-.28	1.87	-.07	1.80	-.08	1.72	.01	1.73	.28	2.01	-.24	1.77	-.66
-.32	.82	.16	.98	-.04	.94	.00	.94	.23	1.17	-.23	.94	-.35
-.25		-1.12		.07		.85		.08		-1.07		-1.90
<u>Plot 3-Ck.</u>												
.50	2.22	-.50	1.72	.23	1.95	.33	2.28	-.53	1.75	.09	1.84	1.16
.23	2.29	.04	2.23	-.05	2.28	.06	2.34	-.13	2.21	-.16	2.05	.75
.54	2.27	-.08	2.19	-.16	2.03	.31	2.34	-.25	2.09	.11	2.20	.79
.18	2.08	-.19	1.89	.01	1.90	.29	2.19	-.32	1.87	.44	2.31	.89
-.03	1.92	-.03	1.89	-.16	1.73	.01	1.74	.22	1.96	.31	2.27	.82
1.42		-.76		-.13		1.00		-1.01		.79		4.41



Appendix 6. (continued).

Depth: Apr. 24: Differ--: May 22: Differ--: June 20: Differ--: July 23: Differ--: Aug. 21: Differ--: Sept. 25: Differ--: Oct. 27													
:	4	:	5	:	6	:	7	:	8	:	9	:	ences : 10
<u>Plot 1-M</u>													
0-6	2.07	0.24	2.31	-1.41	0.90	0.21	1.11	0.15	1.26	0.80	2.06	-0.12	1.94
12	2.46	-.51	1.95	-.29	1.66	-.04	1.62	-.06	1.56	.45	2.01	.22	2.23
18	2.50	-.34	2.16	-.32	1.84	-.12	1.72	-.15	1.57	.29	1.86	.21	2.07
24	2.53	-.14	2.39	-.43	1.96	-.21	1.75	-.15	1.60	.13	1.73	.15	1.88
30	2.50	-.09	2.41	-.30	2.11	-.34	1.77	-.16	1.61	.24	1.85	.00	1.85
36	2.58	-.21	2.37	-.30	2.07	-.17	1.90	-.26	1.64	.31	1.95	-.12	1.87
42	2.60	-.25	2.35	-.21	2.14	-.22	1.92	-.21	1.71	.10	1.81	.17	1.96
48	2.37	-.31	2.06	.05	2.11	-.23	1.88	-.04	1.84	-.05	1.79	.21	2.00
Total		<u>-1.61</u>		<u>-3.21</u>		<u>-1.12</u>		<u>-.88</u>		<u>2.27</u>		<u>-.72</u>	
<u>Plot 2-M</u>													
0-6	1.77	-.29	1.48	-.58	.90	.11	1.01	-.05	.96	1.28	2.24	-.19	2.05
12	2.55	-.69	1.86	-.43	1.43	-.14	1.29	.01	1.30	.97	2.27	-.18	2.09
18	2.42	-.59	1.84	-.25	1.59	-.22	1.37	.00	1.37	.63	2.00	.13	2.13
24	2.52	-.61	1.91	-.24	1.67	-.24	1.43	.08	1.51	.39	1.90	.28	2.18
30	2.62	-.50	2.12	-.45	1.67	-.17	1.50	.07	1.57	.41	1.98	.21	2.19
32.6	1.18	-.32	.86	-.06	.80	-.13	.67	.04	.71	.17	.88	.05	.93
Total		<u>-3.00</u>		<u>-2.01</u>		<u>-.79</u>		<u>.15</u>		<u>3.85</u>		<u>-.30</u>	
<u>Plot 3-M</u>													
0-6	1.89	-.54	1.35	-.45	.90	-.03	.87	0.01	.86	.88	1.74	-.17	1.57
12	2.28	-.60	1.68	-.19	1.49	-.11	1.38	-.05	1.33	.63	1.96	.03	1.99
18	2.36	-.33	2.03	-.39	1.64	-.19	1.45	.02	1.47	.25	1.72	.15	1.87
24	2.39	-.26	2.13	-.43	1.70	-.19	1.51	-.06	1.45	.22	1.67	.01	1.68
30	2.32	-.38	1.94	-.27	1.67	-.13	1.54	-.02	1.52	.12	1.64	.04	1.68
36	2.29	-.60	1.69	.02	1.71	-.14	1.57	-.02	1.55	.08	1.63	.02	1.65
42	1.85	-.16	1.69	.00	1.69	-.09	1.60	-.07	1.53	.01	1.54	.16	1.70
48	1.85	-.15	1.70	-.01	1.69	-.12	1.57	.03	1.60	-.06	1.54	.21	1.75
Total		<u>-3.02</u>		<u>-1.72</u>		<u>-1.00</u>		<u>-1.18</u>		<u>2.13</u>		<u>-.45</u>	

Appendix 6. (continued)

Differ--:Dec. 1:Differ--:Dec. 30:Differ--:Jan. 29:Differ--:Mar. 3:Differ--:Mar. 30:Differ--:Apr. 21: Net												
ences : 11 : ences :		12 : ences :		1 : ences :		2 : ences :		3 : ences :		4 : ences :		:
Plot 1-M												
0.20	2.14	-0.50	1.64	-0.07	1.57	0.54	2.11	-0.76	1.35	0.06	1.41	-0.66
-.32	1.91	.02	1.93	-.14	1.79	.41	2.20	-.35	1.85	-.17	1.68	-.78
-.27	1.80	.21	2.01	-.21	1.80	.02	1.82	.10	1.92	-.18	1.74	-.76
-.07	1.81	.16	1.97	-.10	1.87	.01	1.88	.06	1.94	-.17	1.77	-.76
-.02	1.83	.09	1.92	.16	2.08	-.27	1.81	.13	1.94	-.13	1.81	-.69
-.05	1.82	.14	1.96	.18	2.14	-.26	1.88	.14	2.02	-.13	1.89	-.69
.00	1.96	.12	2.08	.02	2.10	-.01	2.09	-.06	2.03	-.08	1.95	-.65
.03	2.03	-.08	1.95	.11	2.06	-.04	2.02	.09	2.11	-.21	1.90	-.47
-.50		.16		.05		.32		-.65		-1.01		-5.46
Plot 2-M												
.15	2.20	-.24	1.96	-.14	1.82	.28	2.10	-.61	1.49	-.04	1.45	-.33
-.15	1.94	.24	2.18	-.29	1.89	.17	2.06	-.12	1.94	-.27	1.67	-.88
-.38	1.75	.49	2.24	-.47	1.77	.27	2.04	-.10	1.94	-.24	1.70	-.73
-.19	1.99	.23	2.22	-.38	1.84	.13	1.97	-.10	1.87	-.10	1.77	-.75
-.20	1.99	.24	2.23	-.38	1.85	.18	2.03	-.09	1.94	-.17	1.77	-.85
-.04	.89	-.01	.88	-.01	.87	-.01	.86	-.04	.82	-.05	.77	-.40
-.81		.95		-1.67		1.02		-1.06		-.87		-3.94
Plot 3-M												
.32	1.89	-.41	1.48	-.08	1.40	.62	2.02	-.93	1.09	.36	1.45	-.44
-.22	1.77	-.08	1.69	-.10	1.59	.46	2.05	-.46	1.59	.07	1.66	-.62
-.11	1.76	-.04	1.72	-.06	1.66	.07	1.73	-.12	1.61	.10	1.71	-.65
.02	1.70	.06	1.76	-.11	1.65	.08	1.73	-.03	1.70	.02	1.72	-.67
.03	1.71	.02	1.73	-.03	1.70	-.01	1.69	-.01	1.68	.08	1.76	-.56
.00	1.65	.05	1.70	-.06	1.64	.20	1.84	-.17	1.67	.09	1.76	-.53
-.06	1.64	.05	1.69	-.03	1.66	.10	1.76	-.11	1.65	.09	1.74	-.11
-.06	1.69	.03	1.72	-.06	1.66	.06	1.72	-.08	1.64	.06	1.70	-.15
-.08		-.32		-.53		1.58		-1.91		.87		-3.73

Depth: Apr. 24: Differ-: May 22: Differ-: June 20: Differ-: July 23: Differ-: Aug. 21: Differ-: Sept. 25: Differ-: Oct. 27

: 4 : ences : 5 : ences : 6 : ences : 7 : ences : 8 : ences : 9 : ences : 10

Plot 1-H													
0-6	2.18	0.32	2.50	-1.42	1.08	-0.12	0.96	0.44	1.40	0.35	1.75	0.00	1.75
12	2.54	-.56	1.98	-.24	1.74	-.12	1.62	-.11	1.51	.42	1.93	.21	2.14
18	2.27	-.17	2.10	-.25	1.85	-.15	1.70	.08	1.78	-.06	1.72	.21	1.93
24	2.46	-.30	2.16	-.26	1.90	-.17	1.73	.09	1.82	-.17	1.65	.25	1.90
30	2.45	-.27	2.18	-.25	1.93	-.16	1.77	.04	1.81	-.01	1.80	.06	1.86
36	2.48	-.38	2.10	-.19	1.91	-.07	1.84	.02	1.86	.02	1.88	.04	1.92
42	2.48	-.47	2.01	-.07	1.94	-.05	1.89	-.05	1.84	.11	1.95	.05	2.00
48	2.40	-.42	1.98	.08	2.06	-.21	1.85	-.03	1.82	.03	1.85	.05	1.90
Total		-2.25		-2.60		-1.05		.48		.69		.87	

Plot 2-H													
0-6	2.16	- .61	1.55	- .83	.72	.00	.72	.69	1.41	.98	2.39	- .60	1.79
12	2.32	- .45	1.87	- .48	1.39	.02	1.41	.09	1.50	.88	2.38	- .48	1.90
18	2.57	- .53	2.04	- .27	1.77	- .20	1.57	.07	1.64	.76	2.40	- .40	2.00
24	2.53	- .57	1.96	- .11	1.85	- .25	1.60	.07	1.67	.63	2.30	- .26	2.04
30	2.08	- .10	1.98	- .13	1.85	- .10	1.75	- .04	1.71	.60	2.31	- .18	2.13
36	1.95	- .10	1.85	- .02	1.83	- .09	1.74	.04	1.78	.37	2.15	- .12	2.03
37.6		- .03		- .03		- .03		.05		.13		- .05	
Total		-2.39		-1.87		- .65		.97		4.35		-2.09	

Plot 3-H													
0-6	1.74	-.47	1.27	-.37	.90	-.18	.72	-.03	.69	1.34	2.03	.54	1.49
12	2.26	-.50	1.76	-.24	1.52	-.23	1.29	-.02	1.27	.60	1.87	-.20	1.67
18	2.25	-.45	1.80	-.38	1.48	-.25	1.23	.07	1.30	.55	1.85	-.25	1.60
24	2.30	-.46	1.84	-.36	1.48	-.09	1.39	-.03	1.36	.45	1.81	-.28	1.53
30	2.30	-.43	1.87	-.30	1.57	-.19	1.38	-.05	1.33	.48	1.81	-.32	1.49
Total		-2.31		-1.59		-.94		-.06		3.42		-1.59	

Appendix 6. (continued).

Differ--: Dec. 1: Differ--: Dec. 20: Differ--: Jan. 29: Differ--: Mar. 3: Differ--: Mar. 30: Differ--: Apr. 21: Net												
ences : 11 : ences :	12 : ences :	1 : ences :	2 : ences :	3 : ences :	4 : ences :	4 : ences :	4 : ences :	4 : ences :	4 : ences :	4 : ences :	4 : ences :	4 : ences :
Plot 1-H												
0.33	2.08	-0.44	1.62	0.17	1.79	0.52	2.31	-1.05	1.26	0.29	1.55	-0.63
-.23	1.91	-.01	1.90	-.05	1.85	.13	1.98	-.29	1.69	.06	1.75	-.79
-.03	1.90	-.12	1.78	.05	1.83	.07	1.90	-.15	1.75	.00	1.75	-.52
-.01	1.89	-.04	1.85	-.01	1.84	.12	1.96	-.14	1.84	-.11	1.73	-.73
.12	1.98	-.20	1.78	.07	1.85	.11	1.96	-.06	1.90	-.09	1.81	-.64
.07	1.99	-.14	1.85	.06	1.91	.08	1.99	-.04	1.95	-.22	1.73	-.75
.00	2.00	-.12	1.88	.04	1.92	.17	2.09	-.01	2.08	-.15	1.93	-.55
.03	1.93	-.06	1.87	.08	1.95	.06	2.01	-.08	1.94	.00	1.94	-.46
.28		-1.13		.41		1.26		-1.80		-.22		-5.07
Plot 2-H												
.38	2.17	-.38	1.79	-.07	1.72	.27	1.99	-.77	1.22	.31	1.53	-.63
.13	2.03	-.16	1.87	-.11	1.76	.11	1.87	-.17	1.70	-.02	1.68	-.64
-.01	1.99	-.19	1.80	.20	2.00	-.02	1.98	-.07	2.05	-.28	1.77	-.80
-.01	2.03	-.08	1.95	.09	2.04	.01	2.05	-.03	2.02	-.14	1.88	-.65
-.02	2.11	-.11	2.00	-.07	1.93	.08	2.01	-.07	1.94	-.04	1.90	-.18
-.01	2.02	.00	2.02	-.13	1.89	.07	1.96	.00	1.96	-.04	1.92	-.03
-.03		-.04		.01		.05		-.07		.01		-.11
.43		-.96		-.08		.57		-1.04		-.20		-3.04
Plot 3-H												
.39	1.88	-.46	1.42	-.07	1.35	.59	1.94	-.69	1.25	.02	1.27	-.47
.30	1.97	-.31	1.66	-.05	1.61	.10	1.71	-.12	1.59	-.10	1.49	-.77
.13	1.73	-.16	1.57	-.02	1.55	.10	1.65	-.06	1.59	-.02	1.57	-.68
.13	1.66	-.06	1.60	.00	1.60	.06	1.66	-.08	1.58	.06	1.64	-.66
.20	1.69	-.03	1.66	.00	1.66	.02	1.68	-.09	1.59	-.02	1.57	-.73
1.15		-1.02		-.14		.87		-1.04		-.06		-3.31



Appendix 7. Values for the water balance components - Light density plots.

	Plot No.	Sampling Period					
		Apr. 23	May 22	June 20	July 23	Aug. 21	Sept. 25
		to May 22 (5) in.	to June 20 (6) in.	to July 23 (7) in.	to Aug. 21 (8) in.	to Sept. 25 (9) in.	to Oct. 27 (10) in.
Ppt.	1	0.48	0.00	0.06	2.00	5.33	2.47
	2	0.51	0.00	0.09	2.08	5.98	2.26
	3	0.53	0.00	0.06	1.41	5.52	2.04
	Ave.	0.51	0.00	0.07	1.83	5.61	2.26
Int.	1	0.05	0.00	0.01	0.22	0.37	0.20
	2	0.01	0.00	0.00	0.10	0.10	0.05
	3	0.07	0.00	0.03	0.28	0.39	0.18
	Ave.	0.04	0.00	0.01	0.20	0.29	0.14
SRO	1					0.93	0.16
	2					1.21	0.16
	3					0.16	0.16
	Ave.					0.75	0.16
P	1					0.93	
	2					1.21	
Δ SM	1	-0.88	-0.46	-0.05	0.89	0.28	-0.08
	2	-0.98	-0.20	-0.07	0.67	0.80	-0.36
	3	-0.81	-1.75	-0.84	0.08	3.13	-0.28
	Ave.	-0.89	-0.80	-0.32	0.54	1.41	-0.25
Et(s)	1	1.31	0.46	0.10	0.89	2.82	2.35
	2	1.48	0.20	0.16	1.31	2.66	2.41
	3	1.27	1.75	0.87	1.05	1.84	1.98
	Ave.	1.35	0.80	0.38	1.08	2.44	2.25

Appendix 7. Values for the water balance components - Light density plots (continued).

Sampling Period							
Oct. 27 to Dec. 1 (11) in.	Dec. 1 to Dec. 30 (12) in.	Dec. 30 to Jan. 29 (1) in.	Jan. 29 to Mar. 3 (2) in.	Mar. 3 to Mar. 30 (3) in.	Mar. 30 to Apr. 22 (4) in.	Total	
1.30	0.00	0.56	1.91	0.00	0.78	14.89	
1.41	0.00	0.53	1.99	0.00	0.80	15.65	
1.44	0.00	0.52	2.05	0.00	0.72	14.29	
1.38	0.00	0.54	1.98	0.00	0.77	14.94 Ave.	
0.10	0.00	0.04	0.16	0.00	0.08	1.23	
0.05	0.00	0.01	0.05	0.00	0.03	0.40	
0.13	0.00	0.04	0.17	0.00	0.11	1.40	
0.09	0.00	0.03	0.13	0.00	0.08	1.01 Ave.	
						1.09	
						1.37	
						0.32	
						0.91 Ave.	
						0.93	
						1.21	
0.46	-0.60	-0.10	0.44	-0.72	-0.12	-0.94	
0.38	-0.61	-0.03	0.80	-0.90	-0.14	-0.64	
-0.76	-0.54	0.06	0.93	-0.20	-0.93	-1.91	
0.03	-0.58	-0.02	0.72	-0.61	-0.39	-1.16 Ave.	
0.74	0.60	0.62	1.31	0.72	0.82	12.74	
0.98	0.61	0.55	1.14	0.90	0.91	13.31	
2.07	0.54	0.42	0.95	0.20	1.54	14.48	
1.26	0.58	0.53	1.13	0.61	1.09	13.51 Ave.	



Appendix 7. Values for the water balance components - Medium density plots

	Plot No.	Sampling Period							
		Apr. 23	May 22	June 20	July 23	Aug. 21	Sept. 25	Oct. 27	Sept. 25
		to May 22 (5)	to June 20 (6)	to July 23 (7)	to Aug. 21 (8)	to Sept. 25 (9)	to Oct. 27 (10)	to Sept. 25 (10)	to Sept. 25 (10)
		in.	in.	in.	in.	in.	in.	in.	in.
Ppt.	1	0.54	0.00	0.08	2.24	5.25	2.84		
	2	0.53	0.00	0.09	1.71	5.56	2.15		
	3	0.53	0.00	0.06	1.45	5.58	2.04		
	Ave.	0.53	0.00	0.08	1.80	5.48	2.34		
Int.	1	0.14	0.00	0.06	0.57	0.79	0.41		
	2	0.11	0.00	0.05	0.44	0.64	0.28		
	3	0.11	0.00	0.01	0.32	1.16	0.43		
	Ave.	0.12	0.00	0.04	0.44	0.86	0.37		
SRO	1					0.11	0.11		
	2					0.11	0.11		
	3					0.11	0.11		
	Ave.					0.11	0.11		
Δ SM	1	-1.61	-3.21	-1.12	-0.88	2.27	0.72		
	2	-3.00	-2.01	-0.79	0.15	3.85	0.30		
	3	-3.02	-1.72	-1.00	-1.18	2.13	0.45		
	Ave.	-2.54	-2.31	-0.97	-0.64	2.75	0.49		
Et(s)	1	2.01	3.21	1.14	2.55	2.08	1.60		
	2	3.42	2.01	0.83	1.12	0.96	1.46		
	3	3.44	1.72	1.05	2.31	2.18	1.05		
	Ave.	2.96	2.31	1.01	1.99	1.74	1.37		

Appendix 7. Values for the water balance components - Medium density plots (continued).

Sampling Periods							
Oct. 27 to Dec. 1 (11) in.	Dec. 1 to Dec. 30 (12) in.	Dec. 30 to Jan. 29 (1) in.	Jan 29 to Mar. 3 (2) in.	Mar. 3 to Mar. 30 (3) in.	Mar. 30 to Apr. 22 (4) in.	Total	
1.34	0.00	0.59	2.12	0.00	0.80	15.80	
1.44	0.00	0.54	2.05	0.00	0.76	14.83	
1.44	0.00	0.52	2.06	0.00	0.71	14.39	
1.41	0.00	0.55	2.08	0.00	0.76	15.01 Ave.	
0.25	0.00	0.09	0.35	0.00	0.21	2.87	
0.21	0.00	0.07	0.28	0.00	0.17	2.25	
0.29	0.00	0.11	0.43	0.00	0.14	3.00	
0.25	0.00	0.09	0.35	0.00	0.17	2.71 Ave.	
						0.22	
						0.22	
						0.22	
						0.22 Ave.	
-0.50	0.16	0.05	0.32	-0.65	-1.01	-5.46	
-0.81	0.95	-1.67	1.02	-1.06	-0.87	-3.94	
-0.08	-0.32	-0.53	1.58	-1.91	0.87	-3.73	
-0.46	0.26	-0.72	0.97	-1.21	-0.34	-4.38 Ave.	
1.59	-0.16	0.45	1.45	0.65	1.60	18.17	
2.04	-0.95	2.14	0.75	1.06	1.46	16.30	
1.23	0.32	0.94	0.05	1.91	-0.251	15.95	
1.62	-0.261	1.18	0.75	1.21	0.94	16.81 Ave.	

Evapotranspiration in excess of precipitation is caused by variation in soil moisture sampling.

Appendix 7. Values for the water balance components - Heavy density plots.

	Plot No.	Sampling Period					
		Apr. 23 to May 22 (5)	May 22 to June 20 (6)	June 20 to July 23 (7)	July 23 to Aug. 21 (8)	Aug. 21 to Sept. 25 (9)	Sept. 25 to Oct. 27 (10)
		in.	in.	in.	in.	in.	in.
Ppt.	1	0.53	0.00	0.08	2.22	5.28	2.80
	2	0.50	0.00	0.10	1.88	5.57	2.21
	3	0.53	0.00	0.06	1.40	5.58	2.02
	Ave.	0.52	0.00	0.08	1.83	5.48	2.34
Int.	1	0.15	0.00	0.06	0.61	0.89	0.46
	2	0.12	0.00	0.02	0.46	1.35	0.54
	3	0.14	0.00	0.05	0.60	1.15	0.40
	Ave.	0.14	0.00	0.04	0.56	1.13	0.47
SRO	1					0.04	0.04
	2					0.04	0.04
	3					0.04	0.04
	Ave.					0.04	0.04
Δ SM	1	-2.25	-2.60	-1.05	0.48	0.69	0.87
	2	-2.39	-1.87	-0.65	0.97	4.35	-2.09
	3	-2.31	-1.59	-0.94	-0.06	3.42	-1.59
	Ave.	-2.32	-2.02	-0.88	0.46	2.82	-0.94
Et(s)	1	2.63	2.60	1.07	1.13	3.66	1.43
	2	2.77	1.87	0.73	0.45	-0.17 ¹	3.72
	3	2.70	1.59	0.95	0.86	0.97	3.17
	Ave.	2.70	2.02	0.92	0.81	1.49	2.77

¹Evapotranspiration in excess of precipitation is caused by variation in soil moisture sampling.

Appendix 7. Values for the water balance components - Heavy density plots (continued).

Sampling Periods									
Oct. 27 to Dec. 1 (11) in.	Dec. 1 to Dec. 30 (12) in.	Dec. 30 to Jan. 29 (1) in.	Jan. 29 to Mar. 3 (2) in.	Mar. 3 to Mar. 30 (3) in.	Mar. 30 to Apr. 22 (4) in.	Total			
1.32	0.00	0.57	2.15	0.00	0.83	15.79			
1.42	0.00	0.53	2.06	0.00	0.76	15.03			
1.41	0.00	0.52	1.97	0.00	0.73	14.22			
1.39	0.00	0.54	2.06	0.00	0.77	15.01 Ave.			
0.27	0.00	0.10	0.40	0.00	0.28	3.22			
0.35	0.00	0.13	0.50	0.00	0.18	3.65			
0.29	0.00	0.10	0.39	0.00	0.21	3.33			
0.30	0.00	0.11	0.43	0.00	0.22	3.40 Ave.			
						0.08			
						0.08			
						0.08			
						0.08 Ave.			
0.28	-1.13	0.41	1.26	-1.80	-0.22	-5.07			
0.43	-0.96	-0.08	0.57	-1.04	-0.20	-3.04			
1.15	-1.02	-0.14	0.87	-1.04	-0.06	-3.31			
0.61	-1.04	0.06	0.90	-1.29	-0.16	-3.81			
0.78	1.13	0.06	0.49	1.80	0.77	17.55			
0.64	0.96	0.48	0.99	1.04	0.78	14.26			
-0.03 ¹	1.02	0.56	0.71	1.04	0.58	14.12			
0.46	1.04	0.37	0.73	1.29	0.71	15.31			



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