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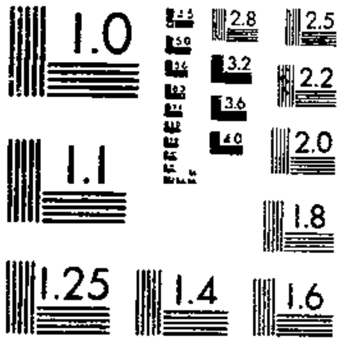

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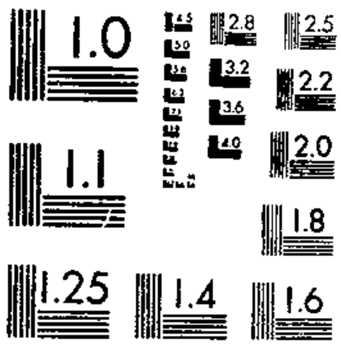

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Disposition of Rainfall in Two Mountain Areas of California[1]

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INTRODUCTION

Knowledge concerning the disposition of rainfall is basic to any plan of land management which has to do with water supply, stream-flow regulation, and erosion control. By disposition of rainfall is meant the processes undergone by rain (and snow) from the time it reaches the earth until it returns to the atmosphere or is delivered into channels, lakes, or underground storage. The processes of rainfall disposition are well known: interception by vegetation, surface runoff, infiltration, evapo-transpiration, percolation through the soil, spring and stream flow, storage in reservoirs, lakes, and seas, and evaporation from water surfaces. But although the processes are recognized, all too little information is available regarding the quantities and rates involved in each of them.

The present study was undertaken to provide quantitative measurements of rainfall disposition in parts of California where controlled water yield is the most important objective of wild-land management.

The measurements had to do with the entry of water into, and losses of water from, the soil mantle of mountain watersheds. Although the quantitative results of this study will be useful primarily in those parts of California in which the study was made, the principles underlying them and the methods presented have much wider application.

SUMMARY

This bulletin reports a study seeking to evaluate and explain some of the hydrologic processes involved in the disposition of rainfall in two mountain areas: One in the Sierra Nevada of cen-

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tral California, the other in the San Gabriel Mountains of southern California. Study of rainfall disposition is basic to an understanding of the role of soil and vegetation in watershed management.

The study had two parts: First, determination of water losses and water yield under natural (undisturbed) vegetation and study of how annual burning and denudation affect losses and yield; second, calculation of the water losses and yield of a watershed.

The first part was conducted on hillside plots. Interception loss and surface runoff were measured, and periodic measurements of soil moisture used to calculate evapo-transpiration losses. Percolation (the water yielded by percolation through the soil mass) was calculated as the difference between rainfall and the sum of surface runoff and the evaporative water losses. Some of the plots were left covered with natural vegetation, some were burned annually, and some were trenched to exclude roots and maintained bare of vegetation.

In the second part, 14 moisture-sampling plots within an 875-acre watershed were studied under natural vegetation. The water yield of the watershed was calculated from the plot results and stream-flow measurements.

Three groups of plots were studied in connection with the first part. At North Fork, in the south-central Sierra Nevada, a group of three was established in 18-year-old woodland chaparral. One of these plots was kept in natural cover, one was burned annually, and one was trenched and maintained bare. Rainfall here ranged from 25 to 60 inches per year. At Bass Lake, some 10 miles from North Fork, three plots were established in 70- to 80-year-old ponderosa pine. Here one plot was kept in natural cover, on one the ground cover (low vegetation and litter) beneath the tree canopy was burned annually, and one was trenched and maintained bare. Annual rainfall ranged from 38 to 59 inches.

On the San Dimas Experimental Forest in southern California four plots were established in 21-year-old brush cover. One of these plots was in mixed chaparral, one in nearly pure hoaryleaf ceanothus, one in nearly pure chamise, and one was trenched and maintained bare. Annual rainfall here ranged from 17 to 48 inches. At all three locations the rainy season normally extends from October into April; the rest of the year is dry.

On the plots with natural vegetation the average annual loss of rainfall due to interception ranged from 5 percent in the woodland chaparral to 12 percent in the ponderosa pine. Interception loss varied from storm to storm, depending upon the quantity of storm rainfall, yet each year it amounted to almost a constant percentage of the rainfall. Rainfall not lost by interception reached the ground, and all but negligible amounts lost by surface runoff or as evaporation from the litter entered the soil.

The quantity of water entering the soil varied directly with annual rainfall. Nonetheless evapo-transpiration losses from each plot were singularly uniform from year to year. Average annual losses ranged from 14 inches in the woodland chaparral to 19 inches in the San Dimas chamise.

A large part of the annual evapo-transpiration loss took place during the spring and summer dry season. The loss during this drying period ranged from 56 percent of the total annual loss in the woodland chaparral to 76 percent of the annual loss in the ponderosa pine. The water thus lost included all water stored in the soil from field capacity to slightly below wilting point and in addition all water added to the soil by the infrequent late spring and summer rains. Under the conditions of winter rain and summer drought typical of these areas the annual evapo-transpiration loss was more strongly influenced by the available water storage capacity of the soil than by any other factor.

As would be expected the quantities of percolation varied from plot to plot in response to soil differences, and from year to year in response to differences in amounts and distribution of rainfall.

On the natural plots rainfall averaging from 10 inches in the woodland chaparral to 19 inches in the San Dimas chamise was required in the early part of each rainy season to raise soil-water storage to field capacity. A large part of this rainfall replaced soil water lost during the preceding dry season; the rest, except for negligible amounts of surface runoff, was lost as interception and as evapo-transpiration between storms.

Percolation began each year when soil-water storage was restored to field capacity and took place during all subsequent storms which added water to the soil in excess of that required to compensate for interstorm losses. The bulk of percolation occurred between December and April, coinciding generally with the period of heaviest rainfall.

Percolation ended each year when rains became too infrequent or too small to replace current evapo-transpiration losses. This marked the beginning of the spring-summer drying period.

Annual burning of the woodland chaparral reduced interception loss, thereby increasing the amount of rain reaching the soil. It also reduced the infiltration capacity of the soil, and thereby greatly increased surface runoff. The net result was that more rain was required each year to start percolation, and the quantity of this flow was greatly reduced. Annual evapo-transpiration, on the other hand, was not appreciably changed by burning. Thus, owing to the reduced interception loss, total water yield of the burned plot (surface runoff plus percolation) was slightly greater than that of the natural plot. However, this increase was achieved at the expense of greatly increased storm flows of surface runoff, often heavily charged with sediment, and correspondingly reduced percolation.

Very much the same results were obtained by annual burning of the ground cover on the ponderosa pine plot. Surface runoff and rainfall required to start percolation were greatly increased and percolation was correspondingly reduced. Annual evapo-transpiration was not significantly changed. As only litter and the sparse low vegetation were destroyed by the burning, it was concluded that interception loss was not appreciably reduced. Hence burning had no significant effect upon the quantity of water yield, but did divert much of this yield into surface runoff.

Removing the vegetation, trenching, and maintaining a bare surface on plots in the woodland chaparral, ponderosa pine, and San Dimas chaparral eliminated all interception and transpiration loss. Surface runoff and soil erosion were greatly increased but evaporative loss of water from the soil was reduced. As a result of the reduced evaporative losses there was a greater carryover of soil water on these plots from one year to the next than was found on the annually burned or natural plots. During each summer the bare soils lost appreciable quantities of water from all depths, but drying was much slower and less complete in the deeper soil layers. Thus the plots with deep soil entered each rainy season with a proportionately greater carryover of water than did those with shallow soil. Total water yield was greatest from the bare plots, but percolation yield was much less than that of the natural plots.

The Monroe Canyon watershed of the San Dimas Experimental Forest, in which the second part of this study was carried on, supports a vegetation composed principally of chamise, ceanothus, and scrub-oak chaparral. The climate, topography, geology, and type of vegetation of this watershed are generally typical of a large part of the brush-covered mountain watersheds of southern California. At the start of soil-moisture sampling, the vegetation had been unburned for 24 years.

The Monroe Canyon soil-moisture plots showed the same characteristics of rainfall dispositon as did the natural plots elsewhere. Of about 31 inches of average annual rainfall some 2.5 inches was calculated as interception loss (on the basis of measurements at the nearby mixed chaparral plots). Combined evapo-transpiration and riparian water loss accounted for 10.8 inches per year. Evapo-transpiration was less in this watershed than in other San Dimas plots because of the lower available water-storage capacity of the watershed soil. Surface runoff was negligible. Percolation through the soil was calculated as 17.8 inches. Of this percolation only 4 inches, or less than one-fourth of the total, left the watershed as measured stream flow. The disposition of the remaining 13.8 inches could not be determined in this study, but it was assumed that most if not all of this water passed into the highly fractured underlying rock and eventually drained from the watershed as underground flow.

In this study the various processes involved in rainfall disposition have been evaluated. The processes are shown to be identical in situations differing as widely as those in the ponderosa pine of the Sierra Nevada and in the chaparral of southern California. However, the quantities involved in each process differ in response to local climate, vegetation, and soil. The study suggests that water accounting of this kind will prove useful in investigations elsewhere in which vegetation and soil treatment are studied in relation to water losses and water yields. This approach should prove especially valuable for determinations of water losses and water yield in watersheds that produce only part of their yield as stream flow and the remainder as underground flow through previous geologic formations.

PREVIOUS WORK

Within the past 20 years research in the hydrologic effects of land-use practices has received tremendous impetus. This has been the result of an increasing consciousness among land managers and research workers of the intimate relation between land use and hydrology. The literature has become so voluminous that no attempt can be made here to review it all. Instead, only certain representative studies will be mentioned, studies which provide a particularly pertinent background to the concepts and conduct of the present study.

Several methods have been proposed for determining watershed yield by keeping a running account of water added to and lost from a watershed. Hursh, Hoover, and Fletcher (*12*)[3] described a monthly accounting procedure used on the Coweeta Experimental Forest in North Carolina. Measured rainfall and stream flow are cumulated by monthly intervals, the difference between them representing the water which remains in storage within the watershed. By means of independent studies, then, the stored water is accounted for in terms of water in the soil, water available for future stream flow, and water lost by evaporative processes. Driebelbis and Post (*5*) made use of a similar accounting procedure on four small watersheds near Coshocton, Ohio. Their rainfall and stream-flow records are supplemented by evapo-transpiration data obtained from periodic soil-moisture sampling, and by percolation data obtained from lysimeters Rowe (*19*) also used an accounting method for determining the effects of land-use practices upon stream flow and flood peaks in California. Because his primary concern was with the influence of land use upon surface runoff, he introduced infiltration rates into the accounting scheme, and found it advantageous to divide the watersheds into zones having uniform hydrologic characteristics. Although this introduction complicates the accounting process, it is necessary because a single land-use practice has different effects upon water disposition when applied on different kinds of soil, or under different environmental or topographic situations.

Many studies have demonstrated the effectiveness of vegetation in protecting the soil against surface runoff (*25*). Also, several studies have shown evaporation losses (interception, evaporation from the soil, and transpiration) to be influenced by the kind, stature, and density of vegetation. Most of these have been well summarized by Kittredge (*14*), who drew several significant conclusions from widespread sources of data. Thus he concluded that in general interception and transpiration increase, and evaporation from the soil decreases, as vegetation increases in stature and density. But, as he pointed out, this is not a hard and fast rule because in semiarid regions transpiration and evaporation may be limited by the availability of soil moisture. In his review Kittredge also commented upon methods used for the measurement of transpira-

[3] Italic numbers in parentheses refer to Literature Cited, p. 82.

tion. He found that methods based upon lysimeter measurements or determinations made upon individual leaves or branches required the application of such large correction factors as to make their usefulness questionable when application was made to whole watershed areas. He suggested that accounting procedures may be more satisfactory as a means of calculating combined interception and evapo-transpiration; and that such procedures can be made more sensitive by judicious periodic soil-moisture sampling.

Hendrickson (*7*) made some excellent suggestions for the conduct of studies designed to measure evapo-transpiration losses from watersheds. He stated that "study of soil-moisture conditions in the field seems to be a method of direct approach to the problem of determining losses from a watershed that will give results that may be used with confidence." He discussed the importance of rating soils for such a study on the basis of their wilting points and moisture equivalents or field capacities, and showed the necessity for expressing soil-water storage in inches depth rather than in percent moisture.

Croft (*4*) included in his study of watershed yield consideration of the amount of water required each year to replenish soil-water storage, which had been depleted by evapo-transpiration during the year previous. By following the penetration of water into the soil he found that the entire soil mantle must be raised to field-capacity storage before increases in base stream flow can take place. For this reason the water lost from the soil by evapo-transpiration prior to the rainy season exerts a powerful influence upon current-season stream flow.

Hoover (*8*) used another approach to the determination of transpiration. After determining by an accounting method the evaporative water losses on a pair of watersheds in the Coweeta Experimental Forest, he cut all the vegetation on one watershed, leaving the cut material spread on the ground to minimize runoff. Transpiration was thus virtually eliminated on this watershed, and annual water yield was increased 17 inches by the cutting. This amount, then, was considered to be a measure of transpiration from the uncut vegetation.

No watershed studies comparable to Hendrickson's, Croft's, or Hoover's have been made in California. Several studies have been made, however, to determine the amount of water lost from chaparral areas and the influences upon this loss of changes made in the vegetation. Veihmeyer and Johnston (*26*) studied fluctuations in soil-water storage under chaparral and woodland-grass vegetation in the northern part of the Sacramento Valley. Plots were established in pairs, one plot of each pair being burned in the fall. Their study showed that when the burned plot had supported primarily nonsprouting vegetation, its water loss during the summer and fall after burning was less than that of its unburned mate. On those pairs of plots which supported mainly sprouting types of vegetation no significant differences in fall storage minima were noted.

Sampson (*21*), working in the same area, obtained similar results and concluded that where differences in water loss were found, the top foot of the burned soil dried more quickly and more thoroughly during the summer, so that the extra water remaining in the burned soil was found only at greater depths.

In Southern California a study of evapo-transpiration was made by Taylor (*24*). Part of his study was conducted on chaparral-covered alluvial fan areas near Upland. From periodic soil-moisture sampling he found that approximately 19 inches of rain must occur to satisfy the field capacity deficit caused by evapo-transpiration of the previous year. The soils he studied were much deeper than those typical of mountain areas, and he found that plant roots removed water from them to a depth of 16 feet. He concluded that on the areas he studied no contributions would be made to the water table if annual rainfall was less than 19 inches. When he carried his studies into mountain watersheds he was concerned primarily with evapo-transpiration in the riparian zone (*2*, pp. 88–121). From a study of stream inflow and outflow along a reach of channel in Coldwater Canyon, he found an evaporative water loss of 54 inches between May and October, the main part of the dry season. This depth of water applied, of course, only to the riparian area, which occupied but a small portion of the watershed.

Bauer (*1*) followed soil-moisture variations in the upland chaparral type of the Santa Monica Mountains, and found, as Veihmeyer and Sampson had found elsewhere, that during the dry summer and fall, soil moisture was reduced by evapo-transpiration to or slightly below the wilting point; that is, all water available to plants was removed from the soil. He also noted that in a fresh burn in this area somewhat more water was found in the soil at the end of summer than was found under unburned chaparral.

Shapiro and deForest (*22*) made use of the cobalt chloride paper method to determine the relative rates of transpiration of a number of common chaparral plants in the Santa Monica Mountains. The measurements they made between September 1930 and March 1931 showed white sage to have the highest rate, and lemonade berry to have the lowest. The other chaparral plants, including important species of ceanothus, oak, and chamise, appeared not to vary greatly in relative transpiration rates.

Some of the research reported in this bulletin formed part of a study conducted by Rowe (*18*, *20*) to determine the influence of woodland chaparral upon soil and water in the Sierra Nevada foothills of central California. Rowe's study, carried on over a period of 9 years, showed that on 1/40-acre plots surface runoff and erosion were greatly increased by burning of the vegetation, and that this increase was the result of a decrease in infiltration capacity of the soil. In his study of the disposition of rainfall on these plots the same soil-moisture sampling approach was used as in the present study. The results indicated that although evapo-transpiration losses were not greatly affected by burning the vegetation, percolation of water through the soil was materially reduced. This reduction was attributable directly to the increased surface flow caused by the treatment. A reduction in interception loss brought about by burning, on the other hand, resulted in a slight increase in total water yield. But this increase was obtained at the expense of flash flows of surface runoff, accelerated erosion, and decreased percolation flow.

THE STUDY AREAS

The present study had two complementary parts. The first was planned to investigate in detail (1) the several processes involved in the disposition of rainfall above, on, and within the soil mantle and (2) the effects exerted upon these processes by annual burning and denudation. This part of the study was made on hillside plots, on which interception loss and surface runoff could be measured and periodic soil-moisture sampling used to calculate quantities of evapo-transpiration and percolation.

The second part was planned to extend the investigation so that the evaporative losses and water yield of an entire watershed could be determined. Periodic soil-moisture sampling in a watershed of 875 acres was supplemented by stream-flow measurements to provide a more complete picture of rainfall disposition than could be obtained from the study of hillside plots alone.

The study was carried on in locations representative of important watershed regions of California: The upper part of the woodland-chaparral zone of the south-central Sierra Nevada Mountains, the lower part of the commercial timber zone of the south-central Sierra Nevada, and the chaparral zone of the mountains of southern California (fig. 1).

The woodland chaparral was represented by plot studies at North Fork, Madera County, 35 miles northeast of Fresno, where Rowe's earlier studies (*18, 20*) were made. The timber zone was represented by plot studies in second-growth ponderosa pine at Bass Lake, Madera County, some 10 miles north of North Fork. The southern California chaparral was represented by plot and watershed studies on the San Dimas Experimental Forest (*16*), Los Angeles County, situated in the San Gabriel Mountains about 30 miles east of Los Angeles.

The climate at all study locations is similar in certain respects. The year is divided into a rainy winter and spring, and dry summer and fall; extremely hot weather is rare, the average summer maximum being about 92° F. at North Fork and Bass Lake and about 85° on the San Dimas area. Winter temperatures rarely drop much below freezing. Amounts and occurrence of annual precipitation vary greatly from year to year, but in each location major storms may be expected at any time between November and March. Precipitation is principally in the form of rain, averaging 33 inches a year at North Fork, 43 inches at Bass Lake, and 30 inches at San Dimas. Snowfall is a rare occurrence at San Dimas except along the highest ridges. In the North Fork area infrequent snow storms may leave as much as a foot of snow on the ground for periods of a week or two. At Bass Lake temperatures are somewhat lower and snowfall is appreciably heavier than in the woodland chaparral area at North Fork. At Bass Lake snowfall comprises about 30 percent of total precipitation. The San Dimas area, being only about

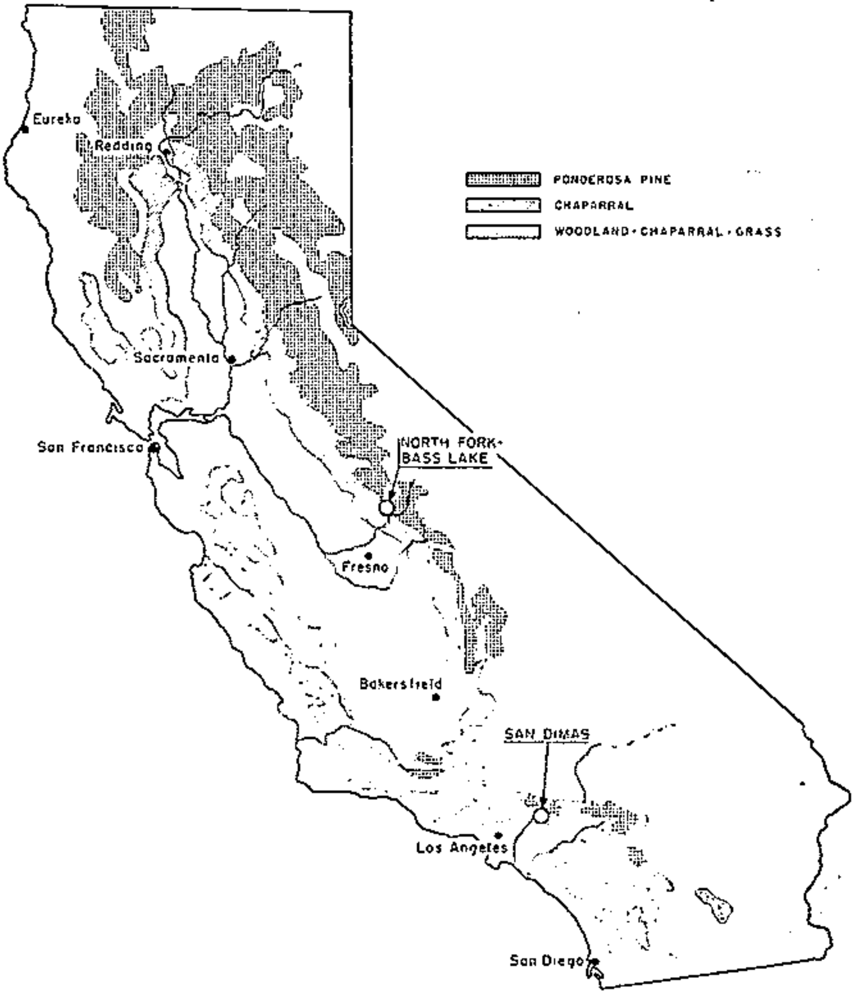

FIGURE 1.—Study areas and vegetation types of California. (Vegetation after Jensen *(13)*.)

40 miles from the ocean, is often blanketed with fog for days at a time during May and June. North Fork and Bass Lake are largely free of fog during this time.

NORTH FORK WOODLAND - CHAPARRAL PLOTS

At North Fork three soil-moisture plots in the woodland chaparral were studied during the period 1936-40 (table 1). The three plots were all located at the same elevation on a single hillside, and lay in a line at roughly 40-foot intervals. Originally all had the same vegetative cover, a mixture of woodland chaparral species, including California buckeye, deerbrush ceanothus, interior live

TABLE 1.—*Characteristics of soil-moisture sample plots by vegetation types*

Original vegetation type, location, and period of study[1]	Number of plots and treatment	Vegetation height	Elevation	Aspect	Slope
		Feet	*Feet*		*Percent*
Woodland chaparral, North Fork, 1936–40.	1 each natural, burned, and denuded.	10–20	2,750	West	32
Second-growth ponderosa pine, Bass Lake, 1940–45.	do.	40–70	3,350	North	40
Mixed chaparral, San Dimas Experimental Forest, 1940–43.	1 natural	10–15	2,800	Northeast	30
Pure hoaryleaf ceanothus, San Dimas Experimental Forest, 1940–43.	do.	10–15	2,800	South	30
Pure chamise, San Dimas Experimental Forest, 1940–43.	1 natural and 1 denuded	5–7	2,800	do.	30
Mixed chaparral, Monroe Canyon,[2] 1943–45.	14 natural	5–20	1,700–3,500	All	40–90

[1] Dates based on hydrologic years, starting Oct. 1 and ending Sept. 30.
[2] In San Dimas Experimental Forest.

oak, buckbrush ceanothus, birchleaf mountain-mahogany, Pacific poison-oak, and Mariposa manzanita. This brush cover was spotted with occasional large trees of Digger pine and California black oak, and interspersed with openings covered with such herbaceous plants as mules-ears, Menzies sanicle, two species of tarweed, and grasses such as the annual bromes and fescues. The vegetation had been burned in 1918 but grew undisturbed until the start of the experiment.

One plot, 20 feet square, was established within this vegetation and designated the "natural" plot (fig. 2, *A*). A second plot of equal size was established in an area that had been burned each fall after 1931. This was the "burned" plot. The burned plot was isolated from the surrounding unburned area by a similarly burned border strip 15 feet wide. In 1935 a trench was dug to bedrock along the outer edge of this border strip to cut intruding roots. The trench was reopened twice thereafter. As a result of the repeated burning before 1936, the buckbrush, manzanita, and part of the deerbrush had been killed. However, annual grasses and herbs germinated after each burn, and these plants together with the regrowth of sprouting shrubs provided some cover in late spring and summer (fig. 2, *B*). In 1936 the burned plot supported a very scattered cover of sprouting brush and a sparse stand of grasses and herbs including annual bromes and fescues, mules-ears, and tarweed (*20, p. 18*). This plot was last burned in the fall of 1937.

Records of rainfall disposition obtained on the burned plot provided measures of the effect of several years of repeated burning followed by 2 years of recovery of the vegetation. By the end of the third growing season after the last burn, the vegetation density was about two-fifths the density before burning.

The third plot, designated as "bare," was located within a 20-foot square that was kept completely clear of all vegetation and litter between the summer of 1936 and the fall of 1940. In 1935 a trench was dug to bedrock (3 to 4 feet deep) around this plot, so as to cut all intruding roots. The trench was refilled but was reopened periodically to prevent roots from growing across it.

The soil of the North Fork area was developed in place by the weathering of granodiorite rock. It is a sandy clay loam belonging to the Holland series and shows little profile development other than an increase in apparent density and a decrease in organic

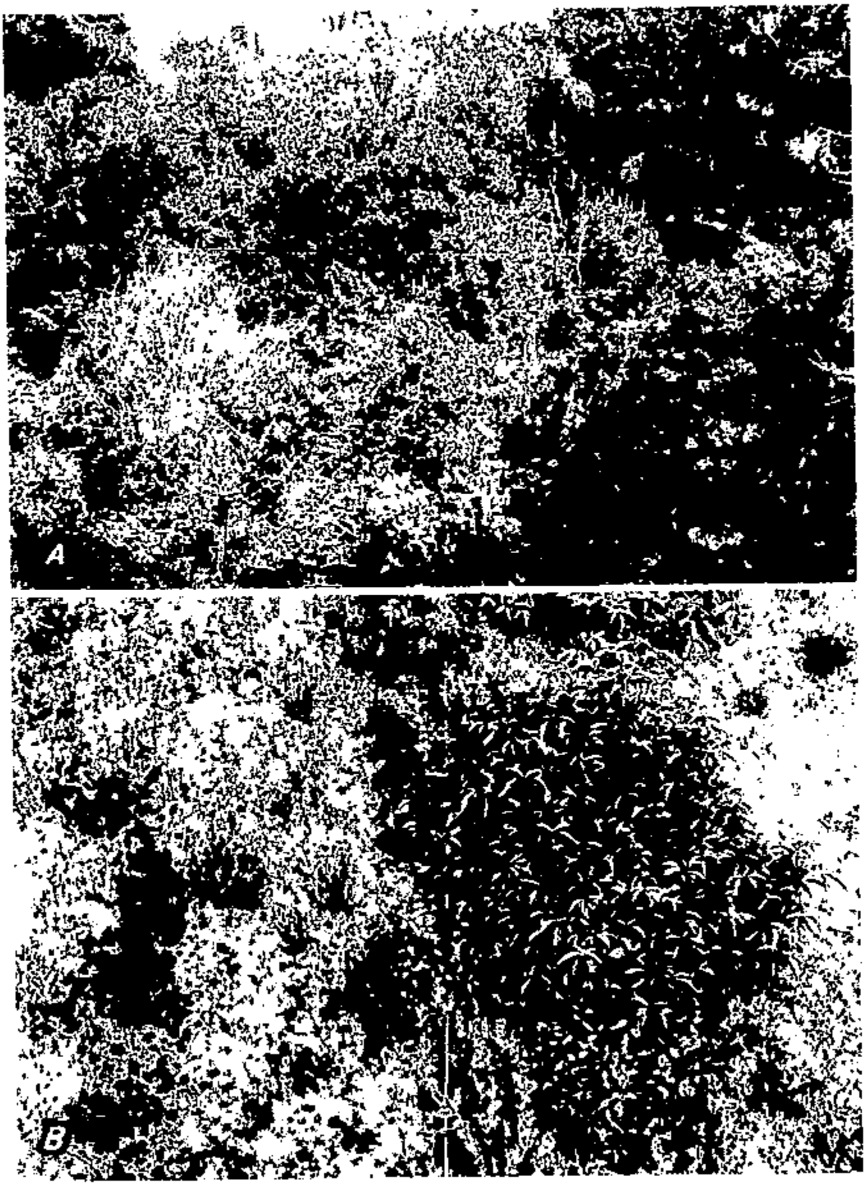

FIGURE 2. North Fork plots in woodland chaparral: *A*, the natural plot; *B*, the burned plot in the late spring of 1937. The angle at which the photograph of the natural plot was taken exaggerates the density of the vegetation.

matter with increasing depth. It averages 40 inches deep to the partly decomposed rock which underlies it. Beneath this layer of compact and relatively impervious weathered material the parent bedrock is massive. The rock mass is intruded occasionally by tightly sealed dikes of pegmatite and aplite. Roots of the shrubs and herbaceous vegetation are concentrated in the upper 30-inch soil depth, but have been observed to penetrate to the weathered bedrock. Under the natural brush the litter cover is fairly complete and averages about ½-inch thick.

For this study the most important soil characteristics are those related to water storage. These are closely similar for the three plots (table 2). Apparent densities were determined as dry weight

TABLE 2.—*Basic soils information for woodland-chaparral, ponderosa pine, and chaparral plots*

WOODLAND-CHAPARRAL PLOTS (NORTH FORK)

Plot treatment and depth of soil layer (feet)	Apparent density	Wilting point [1]	Field capacity [2]	Available water [3]
	gm. /cc.	*Inches*	*Inches*	*Inches*
Natural vegetation:				
0-1	1.31	0.8	2.9	
1-2	1.44	.9	2.9	
2-3	1.52	1.1	3.1	
Total		2.8	8.9	6.1
Burned annually:				
0-1	1.34	.8	2.7	
1-2	1.48	.9	2.9	
2-3	1.53	1.0	3.0	
Total		2.7	8.6	5.9
Maintained bare:				
0-1	1.32	.8	2.8	
1-2	1.45	1.0	2.8	
2-3	1.56	1.3	3.0	
Total		3.1	8.6	5.5

PONDEROSA PINE PLOTS (BASS LAKE)

Plot treatment and depth of soil layer (feet)	Apparent density	Wilting point [1]	Field capacity [2]	Available water [3]
Natural vegetation:				
0-1	1.06	1.1	2.9	
1-2	1.29	1.5	3.2	
2-3	1.54	2.3	4.1	
3-4	1.60	2.7	4.5	
4-5	1.64	2.6	4.4	
5-6	1.66	2.5	4.3	
Total		12.7	23.4	10.7
Burned annually:				
0-1	1.10	1.3	3.6	
1-2	1.30	1.5	3.9	
2-3	1.49	2.8	4.8	
3-4	1.61	2.9	5.0	
4-5	1.62	2.2	4.7	
5-6	1.59	1.7	4.0	
Total		12.4	26.6	14.2
Maintained bare:				
0-1	1.17	1.2	3.4	
1-2	1.38	1.6	3.8	
2-3	1.49	2.5	4.0	
3-4	1.61	3.0	4.8	
4-5	1.68	3.1	5.0	
5-6	1.68	2.6	4.9	
Total		14.0	26.5	12.5

Footnotes at end of table.

TABLE 2.—*Basic soils information for woodland-chaparral, ponderosa pine, and chaparral plots—Continued*

CHAPARRAL PLOTS (SAN DIMAS)

Plot treatment and depth of soil layer (feet)	Apparent density	Wilting point [1]	Field capacity [2]	Available water [3]
	gm/cc	*Inches*	*Inches*	*Inches*
Mixed chaparral:				
0-1	1.24	0.9	2.7	
1-2	1.46	1.1	2.8	
2-3	1.59	1.1	2.9	
3-4	1.69	1.2	3.0	
4-5	1.72	1.2	3.1	
Total		5.5	14.5	9.0
Chamise:				
0-1	1.53	1.2	3.3	
1-2	1.68	1.2	3.6	
2-3	1.75	1.2	3.6	
3-4	1.80	1.3	3.5	
4-5	1.80	1.4	3.4	
Total		6.3	17.4	11.1
Ceanothus:				
0-1	1.36	.9	3.1	
1-2	1.65	1.0	3.2	
2-3	1.75	1.2	3.0	
3-4	1.80	1.1	3.0	
4-5	1.80	1.1	2.9	
Total		5.3	15.2	9.9
Maintained bare:				
0-1	1.53	1.0	3.0	
1-2	1.68	1.3	3.4	
2-3	1.75	1.2	3.6	
3-4	1.80	1.2	3.5	
4-5	1.80	1.2	3.5	
Total		5.9	17.0	11.1

[1] Calculated from 15-atmosphere moisture percentage determined for representative soil samples.
[2] Averages, calculated from 1/3-atmosphere moisture percentages of representative samples, or from moisture percentages of samples from freshly drained soils.
[3] Field capacity less wilting point.

per unit volume of soil cut from the wall of a pit with a constant-volume sampler. Wilting points were assumed equal to the 15-atmosphere moisture percentage of these soils, determined according to the method described by Richards and Weaver *(17)*.[4] Field capacities were determined from the 1/3-atmosphere moisture percentage, following the procedure described by Colman *(3)*. Conversion from percent moisture to inches depth was effected by the use of the equation:

$$\text{Inches depth of water per foot of soil} = \frac{\text{percent moisture}}{100} \times \text{apparent density} \times 12.$$

BASS LAKE PONDEROSA PINE PLOTS

Three study plots were established in 1940 at Bass Lake (table 1). The plots lie within the commercial timber zone, in a fully stocked second-growth ponderosa pine forest, 70 to 80 years old. The principal species are ponderosa pine and incense-cedar; trees on the plots ranged up to 20 inches in diameter and 110 feet tall.

[4] Previous studies conducted on the San Dimas Experimental Forest had showed that the 15-atmosphere moisture content was very close to the wilting point as determined by the classical sunflower method.

Scattered throughout the forest are sugar pine and California black oak. Beneath the forest canopy is a very sparse ground cover consisting of clumps of bear-clover and scattered individuals of small suppressed Mariposa manzanita and Nevada peavine. The forest litter, which provides a virtually complete ground cover, averages 2½ inches thick.

Here, as at North Fork, the three plots (fig. 3) lay at the same elevation on a hillside. They were spaced along a line at intervals of about 50 feet. The natural plot was located within the second-growth timber and received no treatment during the course of the study. The burned plot was in a similar patch of timber through which a ground fire was run in the fall of each year starting in 1938. Thus, each fall the soil was burned clean of the year's accumulated litter, and the ground vegetation was consumed. Between burnings there was a very scattered regrowth of herbaceous plants and an annual fall of pine needles sufficient to cover about 25 percent of the soil surface. No trees larger than 2 inches in diameter were killed by the fires. The bare plot was located in a small opening in the forest, midway between the other two. Here a plot 25 by 40 feet was trenched to bedrock in 1940. A galvanized sheet-iron wall was erected within the trench, reaching from bedrock to within 6 inches of the soil surface, its individual sections locked together so as to present a barrier to root penetration. After the wall was built the trench was refilled with soil. For the whole period of the study this plot was kept bare of vegetation and litter. During early morning and late afternoon the plot was shaded by nearby trees.

The soil of the Bass Lake plots belongs to the Sierra series and is a mixture of residual and colluvial material. It appears to have been developed from the weathering of mixed granodiorite and quartzite rock. The surface foot or so of soil is a fine sandy loam. This overlies a clay loam that grades into fairly tight bedrock at a depth of about 6 feet. The natural plot has a lower field-capacity storage than the others (table 2). Wilting-point storage of the bare plot soil is higher than that of the other two. These differences arise from differences between the three plots in the depth at which the clay loam layer is encountered. In trenching the bare plot few roots were found below the 4-foot soil depth, and none below the 6-foot depth. Apparent densities of the Bass Lake soil were determined as dry weight per unit volume of soil taken from the walls of a sampling pit extending to bedrock.

San Dimas Chaparral Plots

One group of 4 plots on the San Dimas Experimental Forest was established in 1940 near the Tanbark Flat headquarters of the Forest. The other group of 14 plots was established in 1943 in Monroe Canyon, an 875-acre watershed about 4 miles southwest of Tanbark Flat.

One plot near Tanbark Flat was located within a dense stand of mixed chaparral in which hoaryleaf ceanothus, hairy ceanothus, California scrub oak, and birchleaf mountain-mahogany shared

FIGURE 3.—The Bass Lake natural plot (A) and burned plot (B) in the fall of 1942.

dominance. This plot, about 1/100 acre in area, is designated as the "mixed chaparral" plot (fig. 4). The "ceanothus," "chamise," and "bare" plots, each about 1/100 acre in area, were located within a 20-foot radius, about 1/4 mile south of the mixed chaparral plot. This area was selected because of the existence there of natural

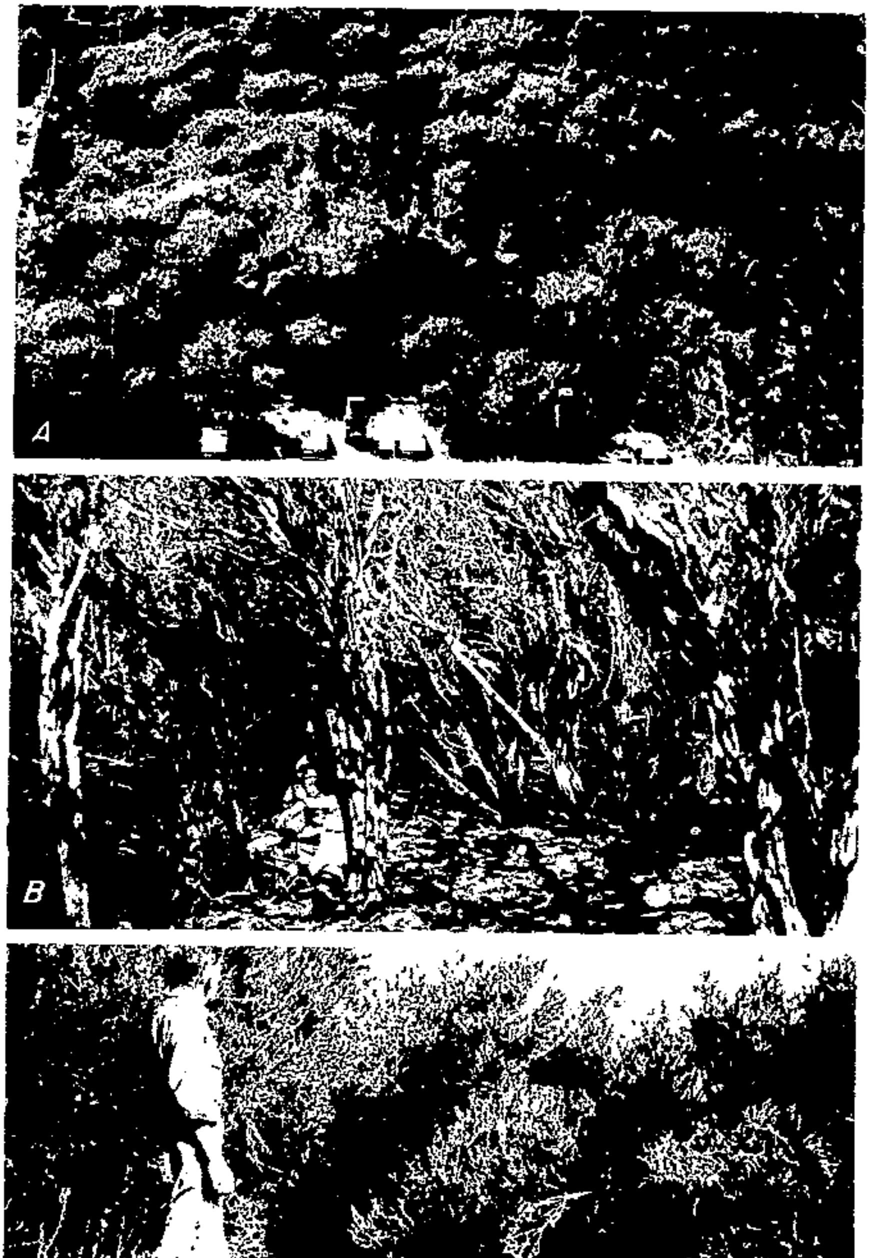

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FIGURE 4.—Vegetation of the San Dimas soil-moisture plots: *A*, Mixed chaparral; *B*, ceanothus; *C*, chamise.

stands of two distinct types of chaparral vegetation. The ceanothus plot lay within a dense stand of hoaryleaf ceanothus which contained only a few scattered chamise individuals. The chamise plot was within a dense stand of chamise which was interspersed with a few individuals of black sage and hoaryleaf ceanothus. The bare plot occupied the center of an adjacent clearing and was maintained clear of vegetation and litter. The periphery of this 20- by 20-foot square plot was trenched to bedrock, all roots cut, and the trench refilled at the start of the study. The trench was reopened once during the course of the study to insure against re-entry of roots.

The area in which these plots were established was last burned over in 1919. Yet the present vegetation has developed into a taller and more luxuriant stand than is usual for chaparral in this locality. This growth may possibly be due to the location of the area, for the topography here is gentler than usual, and the soil is of finer texture and deeper than is typical of most areas in these mountains.

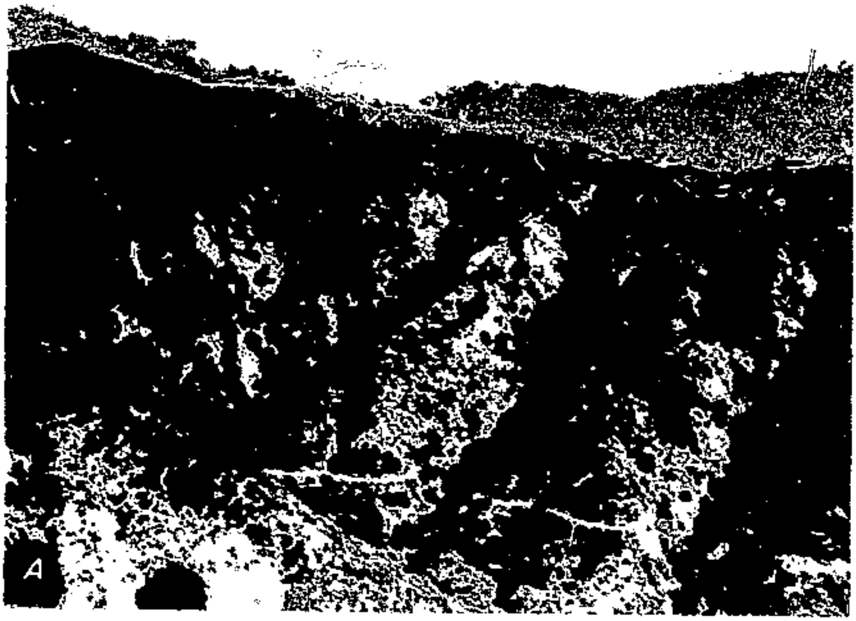
The soil in the Tanbark Flat area is residual, weathered from diorite which is deeply fractured. Shrub roots were concentrated largely in the upper 4 feet of soil but were observed to reach the greatest depths of sampling, and occasionally to penetrate cracks in the bedrock. In the plots the soil mantle averages 5 feet deep; the only evidence of profile development is an increase in apparent density and a decrease in organic matter with depth. The soil is probably closely related to the Holland and Sierra soil series, and has been classified texturally as a sandy clay loam.

The mixed chaparral and ceanothus plots are nearly alike in wilting-point and field-capacity storage, and they are exceeded in both storage values by the chamise and bare plots (table 2). Apparent densities of the San Dimas soils were determined by the constant-volume sample method described in connection with the North Fork plots.

Monroe Chaparral Watershed

The watershed study which forms part of the present investigation was carried on in Monroe Canyon, one of the subwatersheds of the San Dimas Experimental Forest. This canyon is particularly well suited for an initial study of this kind. It is small enough (875 acres) and has a sufficiently small elevational range (1,700 to 3,500 feet) so that it can be studied as a unit; yet it is large enough to have a type of stream flow more characteristic of a large watershed than of a headwater drainage.

The vegetation of Monroe Canyon is representative of that found over much of southern California's mountain lands within the same elevational range (fig. 5). Southerly hillsides are clothed with open to dense stands of the more xerophytic chaparral and sage species, including chamise, hoaryleaf ceanothus, white sage, and black sage. Northerly hillsides are more typically covered with members of the oak-chaparral or oak-woodland associations, which include California scrub oak, hairy ceanothus, and birchleaf mountain-mahogany. Riparian vegetation, including white alder, California sycamore, bigleaf maple, and several species of willows, grows in a narrow strip along the main stream course, but occupies less than 1 percent of the watershed area.



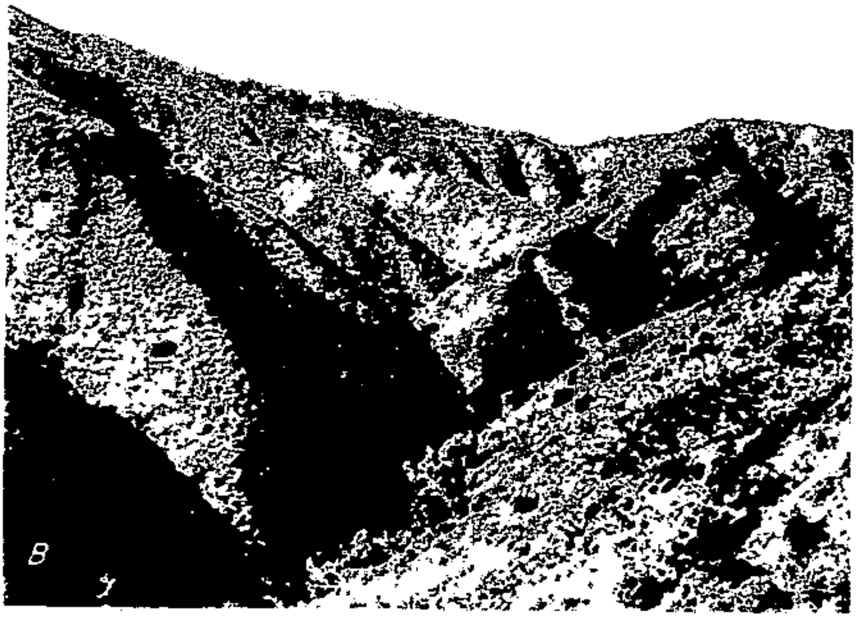


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FIGURE 5.—Vegetation of Monroe Canyon: *A*, Typical east side slopes; *B*, typical west side slopes. The denser oak-chaparral associations of the northerly exposures stand out in contrast to the less dense chamise and sage associations of the southerly exposures.

Geologically this watershed is typical of a large portion of the Sierra Madre Range. Gneisses, schists, and intruded igneous bodies of the San Gabriel formation predominate, these being crisscrossed by numerous large and small faults. The geologic processes under which these mountains were formed have shattered the rocks to great depths and left them very permeable to water, but of very low water-retentive capacity.

The soils of Monroe Canyon (fig. 6) are of two kinds. A narrow band of alluvium flanks the main stream channel, while the watershed slopes are occupied by a residual soil that is relatively homogenous in physical characteristics. The rock-filled sandy loams that predominate on the slopes show no profile development beyond increases in apparent density and decreases in organic matter with depth. Depths to the shattered bedrock range from 0 to more than 6 feet. Shallower soils and numerous rock outcrops are typical of slopes exceeding about 70-percent gradient. Such slopes show evidence of active downhill creep and dry-sliding. The deeper soils usually occupy slopes of lower gradient, which typically have fewer rock outcrops and exhibit less creep.

The soil-water study was started in the fall of 1943 with the establishment of 14 moisture-sampling plots (fig. 6); they are divided into 2 groups—those on southerly hillsides and those on northerly hillsides—because of recognized differences in vegetation. The plots were situated along 2 contour trails which pass through the watershed, one at 2,100 feet elevation, and the other at 3,100 feet. Over the 2-year period of the study, soil samples were obtained within a radius of 5 feet of the center of each plot. Plots were not established in other parts of the watershed because of lack of trails and difficulty of access.

Both field-capacity and wilting-point storage tend to increase as soil depth increases (table 3); however, neither is proportional to soil depth, nor is this relationship at all well defined. The lack of definition is the result of variations in the solid-rock content of the soils in this area, which is independent of soil depth. As rock content increases, the space available for water storage, both at field capacity and wilting point, decreases. In view of these facts field-capacity and wilting-point storage are considered to be more valid criteria of soil characteristics important in this study than are soil depth or texture.

It is pertinent to inquire whether the 14 moisture-sampling plots represent a valid sampling of soil conditions over the watershed as a whole. The sampling can be appraised by comparing soil information from the plots (table 3) with that obtained from a soil survey of this watershed made in 1944.

The 1944 survey provided a detailed description of site and soil for 110 plots located at regular intervals along the two contour trails, the 2,600-foot contour level, and two cleared section lines that cross the watershed in an east-west direction. Pits were dug to bedrock in all but the deepest soils, and measurements of the important profile characteristics were made. Samples taken from the pits were subjected to laboratory analyses for the determination of texture, apparent density, field-capacity and wilting-point storage, and water permeability. Statistical analyses of the survey data failed to indicate any significant relation between these soil characteristics and the measurements used to define the charac-

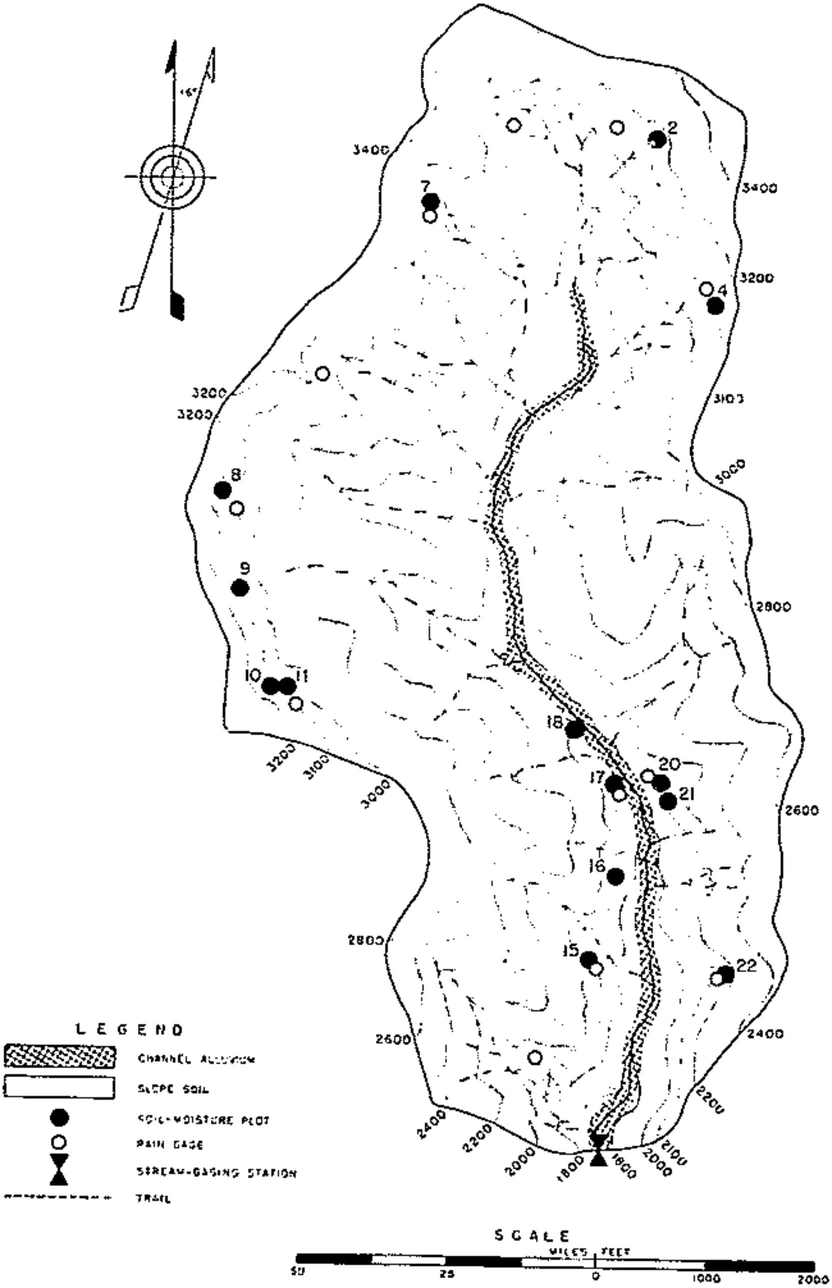

FIGURE 6.—Soils and soil-moisture plots of Monroe Canyon.

TABLE 3.—*Soil and environmental characteristics of moisture plots in Monroe Canyon*

NORTHERLY HILLSIDES

Plot No.	Soil depth	Ele-vation	Slope	Rock content [1]	Mechanical analysis: Sand	Mechanical analysis: Silt	Mechanical analysis: Clay	Water storage: Field capacity [2]	Water storage: Wilting point [3]	Water storage: Available water [4]
	Feet	*Feet*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Inches*	*Inches*	*Inches*
9	3	3,100	90	3	75	19	6	10.4	3.7	6.7
17	3	2,100	90	25	83	13	4	5.2	1.8	3.4
18	3	2,100	90	3	83	12	5	5.8	2.7	3.1
10	4	3,100	70	6	69	24	7	12.6	4.2	8.4
11	5	3,100	70	2	85	11	4	12.4	3.5	8.9
15	5	3,100	90	21	84	13	3	8.0	3.2	4.8

SOUTHERLY HILLSIDES

Plot No.	Soil depth	Ele-vation	Slope	Rock content [1]	Sand	Silt	Clay	Field capacity [2]	Wilting point [3]	Available water [4]
2	3	3,100	60	19	87	11	2	5.8	3.1	2.7
7	3	3,100	85	20	87	9	4	4.8	1.8	3.0
20	3	2,100	100	5	75	21	4	6.9	2.6	4.3
16	4	2,100	75	21	82	15	3	5.8	2.2	3.6
22	4	2,100	90	16	80	15	5	6.4	2.0	4.4
4	5	3,100	40	2	82	12	6	9.2	3.6	5.6
8	5	3,100	60	8	84	12	4	10.7	4.9	5.8
21	5	2,100	75	0	72	23	5	10.4	5.4	5.0

[1] Percent of volume occupied by solid rocks more than 1 inch in diameter.
[2] Determined by field-moisture sampling of freshly drained soil (mean for 2 years).
[3] Based on 15-atmosphere moisture percentage.
[4] Field capacity less wilting point.

teristics of geology, vegetation, and topography. It was decided that if the narrow band of alluvium were excluded, variations in soil characteristics were essentially random. Hence it was concluded that the entire watershed was occupied by a single kind of soil, and that the characteristics of this soil could be determined from the analyses of the 110 pit soils of the survey.

In the following tabulation the soil characteristics pertinent to the soil-water study are compared, using average values obtained from the 110 survey pits and the average of the 14 moisture-sampling plots.

Soil characteristic:		*Average for soil survey*	*Average for 14 soil-moisture plots*
Sand	percent	81	81
Silt	do	16	15
Clay	do	3	4
Field-capacity storage	inches	7.5	8.2
Wilting-point storage	do	3.4	3.2
Soil depth	feet	3	4

This tabulation shows that the averages are nearly the same. From these results it is judged that the soil-moisture plots give a fair representation of conditions on the whole watershed.

METHOD OF STUDY

SOIL-MOISTURE DETERMINATION

To provide the soil-water data required for this study, each plot was sampled for moisture at frequent intervals, using either a

Pozo-type soil tube or a 2-inch post-hole auger. Moisture content was determined by the standard oven-drying and weighing method. The sampling schedule required obtaining soil samples within 72 hours after storm periods, at weekly intervals during the rainy season and early summer, and at 2-week intervals during the late summer and fall when soil-moisture changes had become small. A single hole was dug for each sampling, moisture samples being obtained from it by 6-inch depth increments between the soil surface and bedrock. Through the whole course of the study, sampling was confined to a small portion of the area of each sampling plot, so as to minimize variations in soil texture, density, and organic content, and in exposure of the surface.

The oven-drying method of moisture determination provides a relative rather than an absolute measure of soil-water storage. In this study the absolute measure (inches of water in each foot depth of soil) was required, so that it was necessary to convert moisture percent to inches depth by use of the equation given on page 13.

For the North Fork, Bass Lake, and four San Dimas plots apparent densities were taken from table 2. It was possible to make use of this simple conversion because nearly all of the solid rocks found in these soils (that is, rocks with negligible water content) were small enough to be included both in the moisture and the apparent density samples.

For the Monroe Canyon study a slightly different procedure was used. In several places the soil contained solid rock fragments more than 1 inch thick, too large to be picked up in the sampling auger. It was necessary to correct the water storage calculated from moisture sampling in these places for the amount of space occupied by rocks. This was done by first mapping the edges of the rocks where they intersected the vertical face of a pit dug at the sampling plot, and then calculating the area they occupied on the pit face. The area of rock face expressed as a percent of the total area of the pit face (in each layer measured) was assumed equal to the percent of the volume within each soil layer occupied by solid rock not picked up by the auger. In this case:

$$\text{Inches storage per 12-inch-thick soil layer} = \frac{\text{percent moisture}}{100} \times \frac{\text{percent soil content}}{100} \times \text{apparent density} \times 12.$$

Percent soil content is calculated as 100 minus the rock content.

Other Measurements

Measurements of soil-water storage cannot alone provide a complete accounting of the disposition of rainfall. The investigator must also know how much water is supplied to the soil, and when and in what amounts these additions are made. This requires measurement of precipitation, interception loss from the vegetation, water held on the soil surface as snow, and surface runoff.

Precipitation.—Precipitation was measured in standard 8-inch gages within a few yards of the North Fork, Bass Lake, and San Dimas mixed chaparral plots. The ceanothus, chamise, and bare plots in the San Dimas area were situated so close to Tanbark Flat that rainfall measured at the mixed chaparral plot was considered to apply there also. Monroe Canyon presents a different picture, because the plots there were scattered over a relatively large area. Since 1936 the rainfall in this watershed has been measured by a group of 12 standard gages located along its two contour trails. A study of the rain records showed that the mean catch of these gages provided a close measure of the rainfall at each of the moisture-sampling plots. Annual rainfall from one part of the watershed to another did not vary more than 3 percent about this mean. This represents an accuracy well within the limit of that set by the sampling errors inherent in the determination of soil-water storage. For the Monroe Canyon study, therefore, rainfall was taken as the average of the 12 contour-trail gages.

Interception loss.—Installations were designed specifically for the measurement of interception and stem flow under the vegetation conditions on the North Fork natural plot, the San Dimas mixed chaparral plot, and the Bass Lake natural and burned plots. Descriptions of the North Fork and San Dimas installations, and the results obtained from them, have appeared elsewhere (*6*). At Bass Lake an installation of similar design was adapted to measurements within the forest stand, and provided storm-by-storm interception measurements throughout the study.

At North Fork interception was measured from 1937 to 1940, and at San Dimas in the years 1942 and 1943. For other years of the study interception loss was calculated from the average relation between storm rainfall and interception established by the measurements (fig. 7). Because the vegetation of the North Fork plots was partly deciduous, two interception-loss relations were used, one for fall-winter storms when the deciduous species were leafless and one for spring-summer storms when the vegetation was in full foliage.

No direct measurements of interception loss were available for the ceanothus and chamise plots and the plots in Monroe Canyon. But because the vegetation in these places is generally similar to that at the mixed chaparral plot, it was concluded that no significant error would be introduced if the relation between rainfall and interception loss determined for mixed chaparral were used. Consequently, storm-by-storm interception losses in Monroe Canyon were calculated from mean watershed rainfall, using the relation for the mixed chaparral plot (fig. 7).

No record of interception is available for the burned plot at North Fork. All vegetation on this plot was burned to the ground in the fall of 1936 and 1937. The sparse herbaceous and grass cover which developed after the fire each year did not reach a height of more than a few inches or a density of more than 10 percent until near the end of the rainy season. During the fall and winter, interception by this vegetation was probably negligible. This plot was not burned in 1938 or 1939 so there was some vegetation on the ground through these two rainy seasons. However, as both height and density of this vegetation were low during these rainy seasons, interception losses were probably relatively small. They have been disregarded in the analysis made of this plot.

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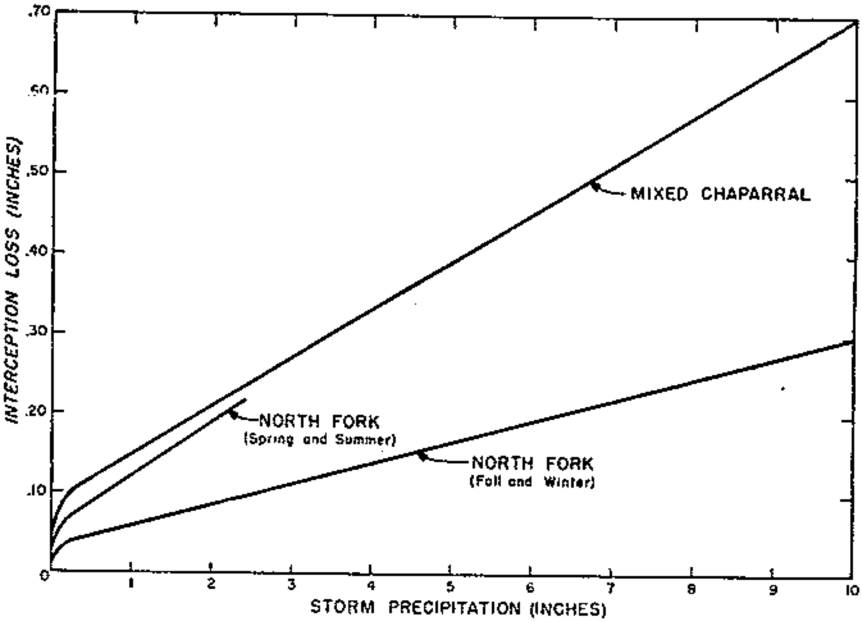

FIGURE 7.—Relation of interception loss to storm precipitation for the woody vegetation of the North Fork and mixed chaparral natural plots, from Hamilton and Rowe (*6*). Equations are:

Mixed chaparral	$IL = .062P + .083$
North Fork, spring and summer	$IL = .070P + .050$
North Fork, fall and winter	$IL = .027P + .031$

(IL = interception loss in inches; P = precipitation in inches.)

Surface runoff.—Surface runoff was measured on specially designed plots, adjacent to and treated in the same way as the soil-moisture plots, as follows:

Plot:	*Years measured*
North Fork:	
Natural	1936–39
Burned	1936–39
Bass Lake:	
Natural	1940–44
Burned	1940–44
Bare	1943–45
San Dimas, mixed chaparral, natural	1940–42

The natural and burned runoff plots at North Fork were 10 feet wide and 110 feet long; they have been described by Rowe (*18, 20*). Identical installations were used for the San Dimas mixed chaparral plot and the natural and burned plots in ponderosa pine at Bass Lake. Runoff from bare soil at Bass Lake was measured by a plot 2 feet wide and 5 feet long, situated in the middle of the bare moisture plot.

In 1936 and 1937 runoff from the bare plot at North Fork was considered equal to that of the adjacent burned plot. This was based upon the fact that the burned plot remained virtually bare of vegetation throughout the greater part of the rainy season. But runoff of the two plots could not be considered equal in 1938 and 1939 because in these years the vegetation on the burned plot was allowed to regrow without disturbance. To determine runoff on the bare plot during these 2 years a curve was developed, as reported by Rowe (*20, p. 36*), showing the average infiltration capacities of the burned plot for the last 3 years during which it had been burned. During 1938 and 1939 runoff from the bare plot was calculated using this average infiltration-capacity curve and the rainfall rates measured during each storm in a nearby recording rain gage.

In the San Dimas area density of vegetation and soil conditions were closely similar on the mixed chaparral, ceanothus, and chamise plots. No measurable amounts of runoff were obtained from the mixed chaparral plot throughout the period of this study, and observations made during the heavy storms indicated that this was very probably true of the other soil-moisture plots as well.

No measurements of surface runoff were made on the bare San Dimas plot during the course of the study, nor on the bare Bass Lake plot until after the first 3 years of sampling. However, observations made during storms, development of rills and erosion pavement on both plots, and measurements of surface runoff made during the last 2 years of sampling on the Bass Lake plot, all indicated the occurence of surface runoff in appreciable amounts. Because of the lack of runoff records, analysis of these two plots, except for the years when runoff was measured at Bass Lake, is necessarily somewhat less complete than that of the others.

Surface runoff from the Monroe Canyon plots was not measured, but was concluded to have been negligible in amount. There were no runoff plots with which this conclusion could have been tested but certain indirect evidence supports it. First, the soil in Monroe Canyon is coarser in texture than that near Tanbark Flat, where runoff plots under natural vegetation yielded no surface flow. Because both vegetation and storm characteristics are much the same in both places it can be concluded that the plots in Monroe Canyon likewise yielded no surface flow. Second, a study of the storm hydrographs of stream flow in Monroe Canyon revealed evidence that during the years of study the volumes of all storm discharges could be accounted for by the amounts of rain intercepted by the stream channel and adjacent bare rock surfaces. However, if surface runoff did occur from any of the plots, it would normally occur during periods of percolation, and would be included in the total water yields as such.

Snow water storage.—Only at Bass Lake was there a sufficiently prolonged period of snow pack to require an accounting of water added to the soil from snow melt. From frequent measurements of precipitation and water stored in the snow pack, the times and amounts of water delivered to the soil were calculated.

Stream flow.—Stream-flow measurements were made only in Monroe Canyon, so only there can results of this study be interpreted directly in terms of stream-flow yields. Float-operated recorders provided a continuous record of water leaving the watershed as channel flow. The stream-gaging station included a V-notch weir for low flows and two flumes for high flows. Diversion of all channel flow into the gaging station was insured by a cut-off wall anchored in the bedrock beneath the channel gravels.

Analysis Procedure

The data used in the analysis of rainfall disposition were made up of the following elements:

1. A running record of water stored in the soil, expressed both in inches depth for each foot-thick layer, and in inches depth for the whole depth of soil;

2. Storm-by-storm records of precipitation, interception loss, snow-pack water (at Bass Lake only), surface runoff, and water entering the soil surface.

These elements must be related in time and quantity for a satisfactory and useful analysis. This was acomplished as follows:

1. Each year was separated into periods representing the observed soil-water storage cycle: One period of wetting, one of sustained high storage, and one of drying. This was done so that attention could be concentrated on the soil-water conditions of greatest hydrologic significance in each period. During the wetting period, which starts with the beginning of the rainy season, the most important hydrologic features exhibited by the soil are its progressive downward wetting (increasing storage) resulting from successive storms, the evaporative water losses between storms, and the time when the soil mantle is wet to field-capacity storage to its base. During the high storage period (hereafter called the percolation period), percolation, evaporative losses, and the replacement of these losses by rainfall, are the more significant features. During the drying period, the rates and amounts of evaporative water loss are of primary concern, all current rainfall entering the soil being evaporated.

2. Prior to each storm in all periods the trend of water storage shown by sampling since the previous storm was carried forward to the start of the current storm; increases in storage were thus associated with the storm which produced them. These increases usually agreed satisfactorily with the rainfall measured as having entered the soil. However, when the discrepancy was great and could not be explained a correction was made in the water-storage figure so as to bring water entry and storage increase into agreement. Small storms that occurred during the drying period or during prolonged intervals of drought in other periods caused no measurable increases in soil-water storage. These storms wet the soil only a few inches deep, and as a consequence of water losses taking place from greater depths, produced no apparent increase in water storage for the soil as a whole. Water added to the soil by

these small storms was quickly returned to the atmosphere. Therefore, such water was included in the quantity assigned to evapo-transpiration.

3. Soil water was considered to be available for evapo-transpiration during all intervals between storms but no allowance was made for evapo-transpiration during periods of rainfall. It has already been stated that the water-storage trend measured after a storm was extended forward to the start of the next storm. When necessary, the trend was carried back to the end of the previous storm. This extension generally covered only a day or two so that the errors in estimating evapo-transpiration by this simple extrapolation were very small. Annual evapo-transpiration was calculated as the cumulated losses of soil water shown by sampling between storms plus the losses measured during the drying periods.

4. Percolation was calculated each year as the difference between the rainfall and the sum of surface runoff plus evaporative water losses plus any decrease, or minus any increase, in soil-water storage at the end of the year. The calculation of annual percolation is illustrated by the equation:

$$\text{Percolation} = \text{Rainfall} - (\text{interception} + \text{runoff} + \text{evapo-transpiration}) - (\text{minimum storage at end of year} - \text{minimum storage at start of year}).$$

For plots from which surface-runoff records were unavailable, there was no way of separating water that entered the soil during the percolation period from that which ran off the surface. Therefore, percolation and runoff were combined for these plots.

It is apparent that evapo-transpiration is undermeasured and percolation is correspondingly too great by an amount equal to the quantity of water drawn upon by evapo-ransptiration from the rock beneath the soil. Soil-moisture sampling was carried to bedrock, but in deep pits dug at some of the sampling locations occasional roots were observed to penetrate into crevices in the hard rock below the sampling depths.

Determinations made in the course of the Monroe Canyon study showed that the fractured rock immediately underlying the soil could hold no more than 0.05 inch of water available to plants per foot of rock depth. This water was held in rock crevices filled with weathered material and in the crushed-zones of faults. The amount of water was small because of the small proportion of the total space occupied by these openings in the rock and the coarse texture of the included weathered material. The rock underlying the soil at North Fork and Bass Lake was much less heavily fractured than that in the San Dimas area; hence even less water was available to plant roots that may have penetrated below the soil at these two locations.

No information is available regarding the maximum depth of penetration of chaparral roots. But even if those in Monroe Canyon penetrated, and absorbed moisture through 20 feet of rock depth, they would not have more than 1 inch of water available to them from this source.

RESULTS OF THE STUDY

The results of this study of rainfall disposition are taken up in two parts. In the first part the plot studies at North Fork, Bass Lake, and San Dimas will be discussed. The second part will be devoted to analysis of the 14 plots in Monroe Canyon and to the interpretation of results obtained from them in terms of rainfall disposition over this watershed as a whole.

RAINFALL DISPOSITION ON PLOTS

The objective of the plot studies was twofold: To follow the disposition of rain from the time it reaches the ground until it leaves the soil as percolation or evapo-transpiration; and to learn what changes in this disposition result from differences in location of the plots, in natural vegetation, and in treatment of vegetation. Thus water itself becomes the material of primary interest; and it is in terms of water that the results of the study will be discussed. In these terms the behavior of all the plots was strikingly similar in a number of ways. Hence detailed study of the soil-water storage cycle of but one of the plots through a single year gives an understanding of rainfall disposition that applies in a general way to all the other plots and years considered in this investigation.

NORTH FORK WOODLAND CHAPARRAL

The North Fork natural plot and the year 1939–40 have been selected for detailed discussion. For this analysis the hydrologic year was considered flexible in length, starting with the first fall rain of one year and ending with that of the next. In this way all rainfall can be properly assigned to the year in which it reaches and is lost from the soil.

The soil-water cycle.—Prior to the first rain of the year water storage was at a minimum at all depths in the soil (figs. 8 and 9). The first rain and those following during the next few weeks were sufficient to cause important increases in storage within the upper 2 feet of soil, but the third foot received only enough water to wet it part way through. Before the next rain fell, in early December, a considerable loss of stored water had taken place by evapo-transpiration. No percolation through the soil mantle could have taken place between September and December because the third foot layer had not yet been brought to field-capacity storage. This situation prevailed until the storm of January 1 to 4, which brought just enough rain to the soil (3.9 inches less 0.2 inch of interception loss) to raise all layers to field-capacity storage. The time covered from the start of the rainy season up to and including this storm is considered the wetting period of the water-storage cycle.

During the 3-month period which followed (January 4 to April 4), storms were sufficiently frequent and brought enough rain to maintain soil-water storage close to field capacity and to replace water lost by evapo-transpiration between storms. Percolation during this period was the amount of precipitation entering the soil that was not offset by evapo-transpiration. Only during the

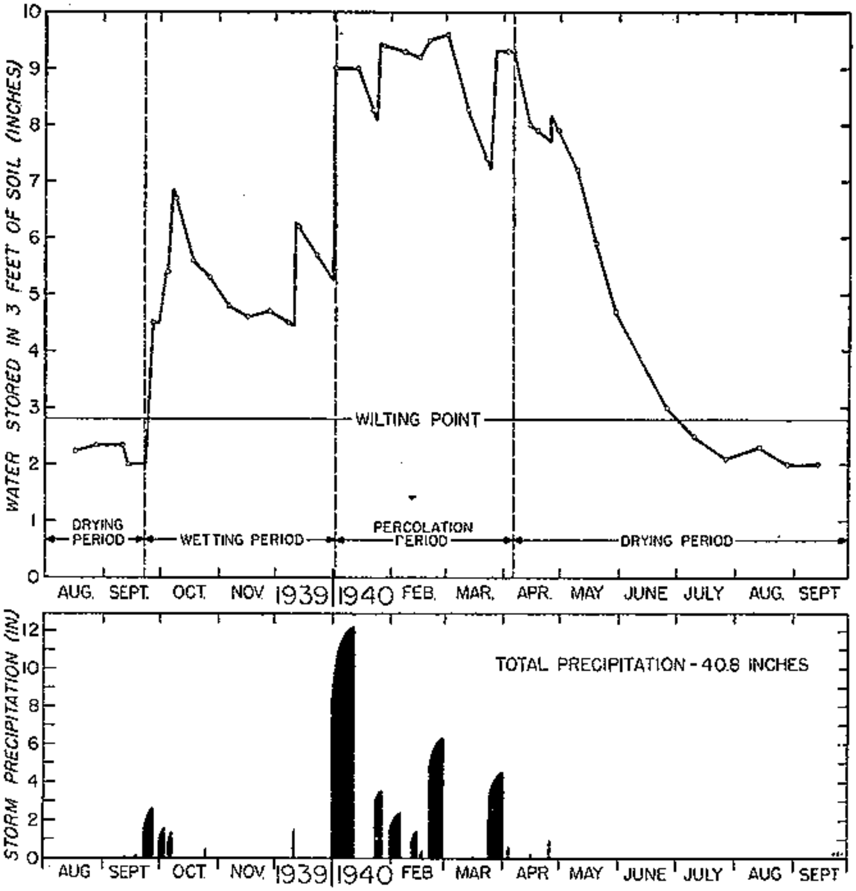

FIGURE 8.—Seasonal variations in storage of water in the soil of the North Fork natural plot, 1939-40.

percolation period and the last storm of the wetting period can percolation take place. During the remainder of the year some part of the soil mantle is always below field-capacity storage, so that rains occurring then do not produce percolation. Evapo-transpiration took place from all depths of the soil (fig. 9). This indicates that plants were drawing upon water stored throughout the soil mantle.

The end of the percolation period was indicated, not by the real end of rainfall for the year, but by the time when rains became so infrequent and storms so small that they failed to replace losses caused by evapo-transpiration. The drying period, which started with the end of the last percolation-producing rain, was characterized by progressive drying of the soil at all depths and loss by evapo-transpiration of such late spring, summer, and fall rains as occurred. During the early part of the drying period

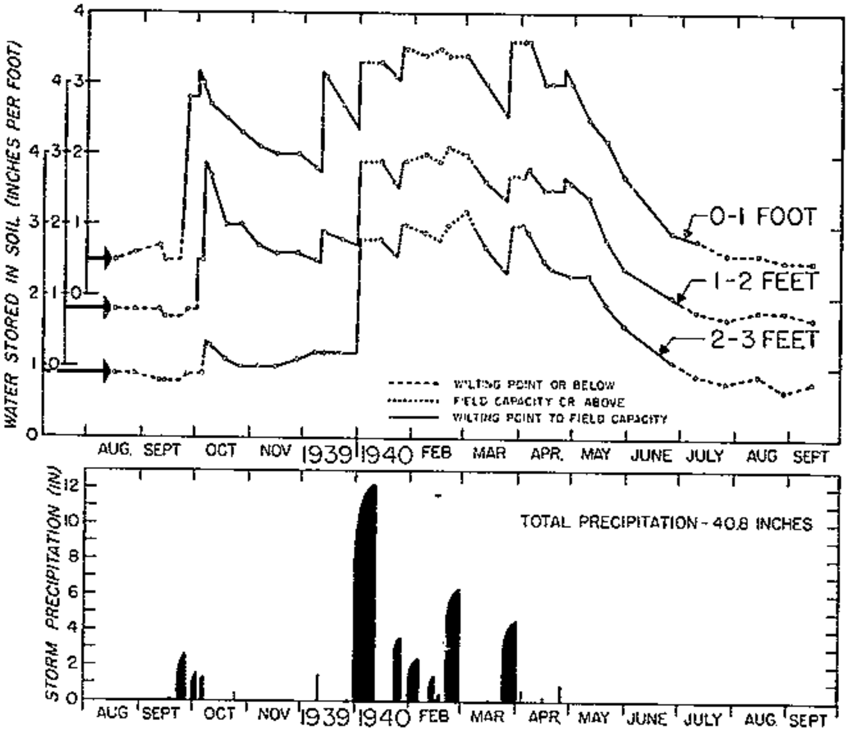

FIGURE 9.—Seasonal variations in storage of water in foot-by-foot soil depths of the North Fork natural plot, 1939-40. (Variations in soil-water constants—wilting point and field capacity—throughout the year are due principally to variations in the physical characteristics of the soil from sampling spot to sampling spot.)

evapo-transpiration losses were rapid; rates tended to be somewhat greater in the upper than in the lower part of the soil. These rate differences with respect to depth were more marked in the 1939–40 year than in some other years because rain, in late April 1940, increased storage in the upper 2 feet of the soil. In years when rains of this kind did not occur there were smaller differences in loss rates between the several soil layers.

Water-loss rates decreased markedly at about the time when each soil layer reached wilting-point storage. This was true of all the vegetated plots studied. It seems probable, from this information, that the woody vegetation on these plots can draw little if any more water from the soil than can herbaceous plants, which are known to suffer from lack of water when soil moisture has been depleted to the wilting point. Yet the woody plants involved in this study do not die, even when exposed to soil having less than wilting-point storage for months at a time (nearly 3½ months for 1940). During such periods the plants cannot obtain any significant quantity of water from the soil, nor is any appreciable amount available to them from the underlying rock. Therefore it must be assumed for the present that these plants survive the summer drought by entering some type of dormant state. This assumption is supported by the observation that chaparral shrubs grown in soil confined in lysimeters at San Dumas have survived even though the moisture content of the confined soil remained below the wilting point for as long as 5 months at a time.

By the end of the drying period soil-water storage once more reached the minimum of the previous year, about 0.8 inch less than the wilting-point storage of the soil. This wilting-point deficit was about equally distributed through the soil: 0.3 inch in the top foot, 0.2 inch in the second foot, and 0.3 inch in the third.

Despite a wide range in annual rainfall, the soil-water storage characteristics in other years were very nearly the same as in 1939-40 (table #4). Minimum storage was close to 2.0 inches, 0.8 inch below wilting-point storage. Field capacity ranged from 8.5 inches to 9.3 inches, and the mean difference between minimum and field-capacity storage indicates that more than 6.8 inches of rain would have to enter the soil in a single storm in order to produce percolation through the soil at the start of the rainy season. Actually, 7.5 inches to 11.7 inches of rain were required to bring the soil to field-capacity. This difference is due, of course, to the fact that several storms occurred in each wetting period and that between these storms storage was reduced by evapo-transpiration.

TABLE 4.—*Soil-water characteristics and rainfall disposition for the North Fork natural plot,[1] 1936-40*

SOIL-WATER CHARACTERISTICS

Item		1936–37	1937–38	1938–39	1939–40	Average
Minimum storage (start of year)	inches	2.0	2.0	2.1	2.2	[2]2.1
Wilting point less minimum storage [3]	do	.8	.8	.7	.6	[3].7
Field-capacity storage [4]	do	8.5	8.8	9.0	9.3	8.9
Field capacity less minimum storage	do	6.5	6.8	6.9	7.1	6.8
Rain to start percolation	do	8.9	7.5	11.7	11.4	9.9
Mean evapo-transpiration rate:						
Wetting period	inches per day	.005	.004	.027	.040	.020
Percolation period	do	.100	.068	.070	.058	.074
Entire soil below wilting-point storage	days	146	89	75	105	104

RAINFALL DISPOSITION (INCHES)

Item	1936–37	1937–38	1938–39	1939–40	Average
Rainfall	40.7	60.1	24.6	40.8	41.5
Interception loss	2.2	3.1	1.5	2.1	2.2
Surface runoff	0	0	0	0	0
Rainfall entering soil	38.5	57.0	23.1	38.7	39.3
Evapo-transpiration	11.7	14.4	14.7	15.7	14.1
Percolation	26.8	42.5	8.3	23.2	25.2

[1] Calculations based on 3-foot soil depth.
[2] Average includes minimum storage measurement of 2.0 inches at start of 1940-41 hydrologic year at which time sampling was discontinued.
[3] Wilting-point storage = 2.8 inches.
[4] Variations between years in field-capacity storage are due in part to variations in physical characteristics of successive soil samples and in part to experimental error.

Evapo-transpiration rates can be grouped conveniently according to whether the water losses take place during the wetting or percolation periods. A considerable range of rates was found between different storm-to-storm intervals. However, no consistent or pronounced trend in these rates was detected, so that the average rate of each period was considered the most applicable one. This rate was calculated as total evapo-transpiration divided by total days between storms during the period. Lower rates for the wetting periods in 1936–37 and 1937–38 were undoubtedly due to more concentrated rainfall and the shorter duration of the wetting period in these years. For the 4 years studied the average evapo-transpiration rate during the wetting period was 0.02 inch per day, and during the percolation period 0.074 inch per day.

It was mentioned earlier that the soil mantle of this plot was entirely without water available to plants (that is, below wilting-point storage) for nearly 3½ months in the summer and fall of 1940. In other years the soil mass was entirely below the wilting point for from 2½ to nearly 5 months (table 4). The similarity of the summer drying portion of each year's water-storage cycle is immediately apparent when the drying curves are moved in point of time so that in all years the drying period is entered on the same day (fig. 10). Closer coincidence is prevented chiefly by wetting due to occasional summer rains. In all years loss rates decrease gradually as wilting-point storage is approached and then decline sharply, becoming virtually zero soon after storage drops to the wilting point. In general wilting-point storage is attained within 2 or 3 months after the start of the drying period, and nearly constant minimum storage is reached within 2 months thereafter.

Rainfall disposition.—Now, with reference to table 4, it is possible to study the disposition of precipitation for this plot. Roughly 5 percent of each year's precipitation was returned to the atmosphere as evaporation of rain intercepted by the vegetation canopy. Surface runoff was never more than a trace. Therefore, the precipitation measured as entering the soil was approximately 95 percent of the total precipitation, varying from 23 to 57 inches for the years studied. Despite this great range in water entry, the measured evapo-transpiration losses were singularly uniform and, furthermore, appeared to bear no relation to quantity of annual rainfall. This is the direct result of the seasonal nature of the rainfall. There is a relatively small range in the quantity of rain required to raise soil-water storage to field capacity (table 4). This range is primarily a function of the quantity of rainfall per storm and the time elapsing between storms. Summer and fall storms do not account for more than 2 inches of the year's precipitation, yet during this dry season a large part of the year's evapo-transpiration takes place. The bulk of the rain usually falls during the percolation period when much of it flows through the soil. This is why evapo-transpiration varied little while percolation varied greatly in response to differences in annual rainfall.

Effect of Burning

The burned plot at North Fork, it will be recalled, was burned in the falls of 1936 and 1937. In the years 1938–39 and 1939–40 vegetation on this plot was allowed to grow without disturbance. Hence, the burned plot must be considered in two stages: The 2 years during which it was burned in the fall, and the 2 years during which it recovered.

The minimum water storage of soil on the burned plot was only slightly higher, during the two burning years, than that of the natural plot. It dropped each year 0.5 inch below wilting-point storage, as compared with 0.8 inch on the natural plot (tables 4 and 5). This difference was due almost entirely to a slightly smaller decrease below wilting point in the third foot of the burned plot than in the corresponding layer of the natural plot soil. With the return of vegetation during the next 2 years, however, minimum storage dropped even farther below the wilting point on this plot than it did on the natural plot. This was the result of greater losses from the top foot of this plot (because of more complete drying of this sparsely covered soil) combined with

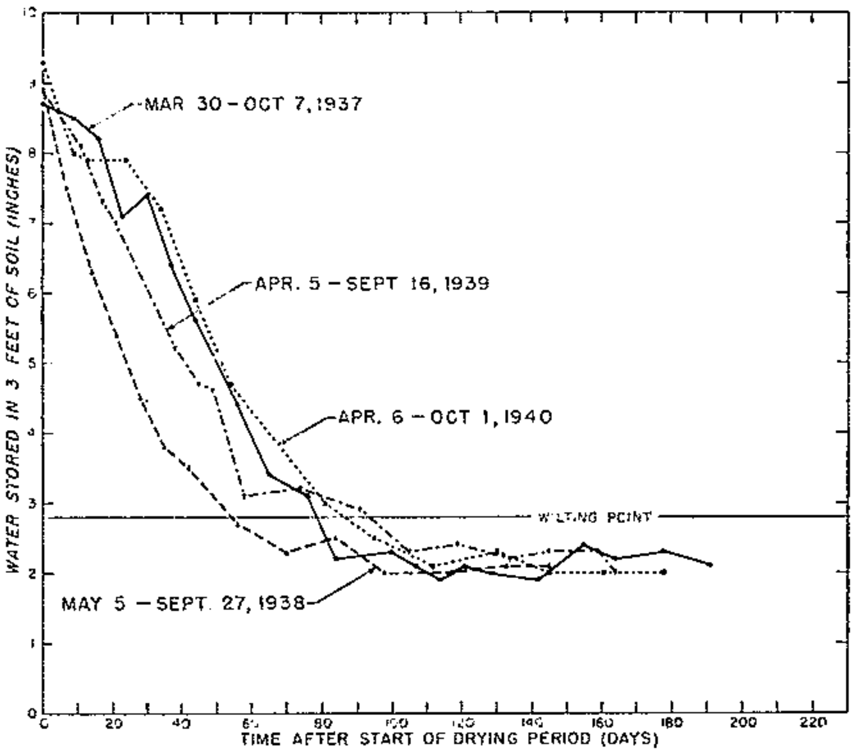

FIGURE 10.—Water storage in the soil of the North Fork natural plot during the drying periods, 1936-40.

TABLE 5.—*Soil-water characteristics and rainfall disposition for the North Fork burned plot,*[1] *1936-40*

SOIL-WATER CHARACTERISTICS

Item	Burned		Unburned since 1937		Average	
	1936–37	1937–38	1938–39	1939–40	1936–38	1938–40
Minimum storage (start of year) ....inches	2.2	2.2	2.2	1.8	2.2	[2] 1.9
Wilting point less minimum storage [3] ......do	.5	.5	.5	.9	.5	.8
Field-capacity storage ......do	8.6	8.5	8.6	8.6	8.6	8.6
Field capacity less minimum storage ......do	6.4	6.3	6.4	6.8	6.4	6.6
Rain to start percolation ......do	9.8	13.2	12.0	11.4	[4] 11.5	[4] 11.7
Mean evapo-transpiration rate:						
Wetting period ......inches per day	.014	.004	.033	.037	.009	.035
Percolation period ......do	.072	.067	.098	.053	.070	.076
Entire soil below wilting-point storage...days	119	([5])	34	95	[4] 60	[4] 64

RAINFALL DISPOSITION INCHES

Item	1936–37	1937–38	1938–39	1939–40	1936–38	1938–40
Rainfall	40.7	60.1	24.6	40.8	50.4	32.7
Interception loss	([6])	([6])	([6])	([6])	([6])	([6])
Surface runoff	6.8	23.8	1.6	.6	15.3	1.1
Rainfall entering soil	33.9	36.3	23.0	40.2	35.1	31.6
Evapo-transpiration	11.2	13.2	17.2	15.7	12.2	16.4
Percolation [7]	22.7	23.1	6.2	24.7	22.9	15.4

[1] Calculations based on 3-foot soil depth.
[2] Average includes minimum storage measurement of 1.6 inches at start of 1940–41 hydrologic year at which time sampling was discontinued.
[3] Wilting point storage = 2.7 inches.
[4] Differences between two periods not significant owing to variations in rain occurrence.
[5] Third foot above wilting point.
[6] Not measured.
[7] Includes any interception loss of the percolation period.

equal losses from the two plots at greater depths. At the end of the second year of recovery, the soil of the burned plot held only 1.6 inches of water, a deficit of 1.1 inches below the wilting point.

Field-capacity storage was about the same on this plot as on the natural plot. The small differences in minimum storage between the two made for only minor differences in field-capacity deficit (field capacity less minimum storage) at the start of each year. However, more rain was required in every year but the last to raise the soil of the burned plot to field capacity. This was because surface runoff, during the wetting period on the burned plot, amounted to 2.5 inches in 1936–37, 6.4 inches in 1937–38, and 1.0 inch in 1938–39. These quantities are more than enough to offset the rainfall losses caused by interception on the natural plot, which yielded no surface flow. In 1939–40 the 0.3 inch of runoff occurring during the wetting of the burned plot corresponded to a loss from the natural plot of 0.3 inch by interception.

Evapo-transpiration rates were not significantly different between the two plots, when compared year by year (tables 4 and 5). Wetting period rates appear to have been lower during the first 2 years on the burned plot than during the other two, yet a similar sequence is shown by the natural plot. Therefore the change cannot be considered a result of annual burning or subsequent recovery. During the percolation periods there were again

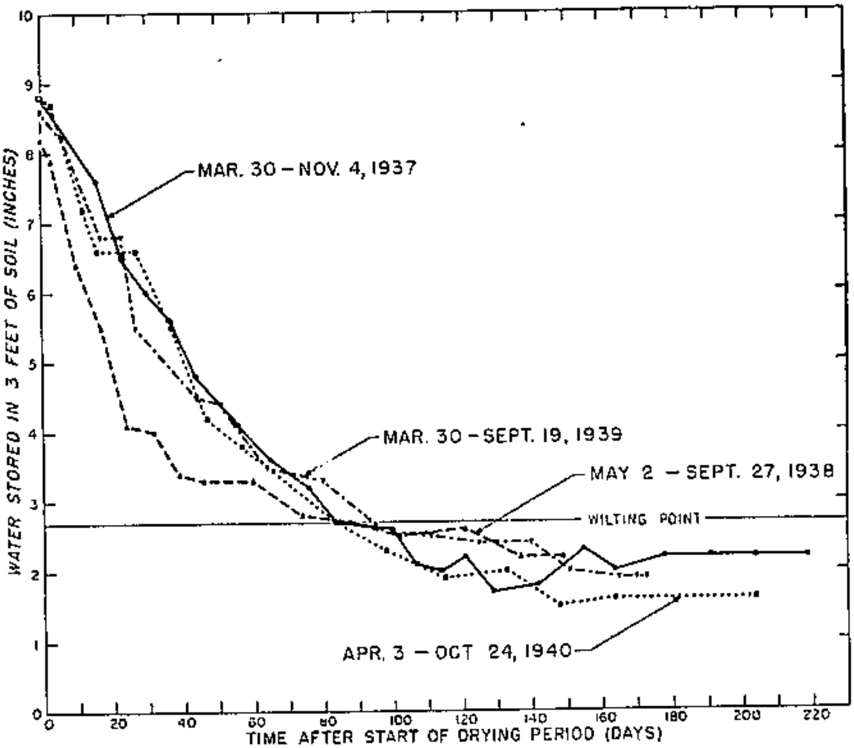

FIGURE 11.—Water storage in the soil of the North Fork burned plot during the drying periods, 1936-40.

only small differences in this rate. In view of the limits of error to which this study is subject, these differences in evapo-transpiration rates cannot be considered significant.

The somewhat slower drying of the lower half of the burned plot, compared with the natural plot, is reflected in the shorter time each year during which this plot was entirely below wilting-point storage. In 1939–40 the difference in time had become very small, a definite response to regrowth of the vegetation.

The summer drying curves of the burned plot (fig. 11) are strikingly similar to those of the natural plot. In fact, this similarity is so close that if the two sets of curves are superimposed they are almost indistinguishable. The principal difference seems to be that in the burned plot wilting-point storage for the soil as a whole is reached within about 3 months after the end of the percolation period, while in the natural plot it is reached in about 2½ months.

The hydrologic effects of burning become apparent when the disposition of rainfall is studied (table 5). Interception loss, as has already been mentioned, was not measured, but it is assumed to have been small. If this loss is disregarded, about 5 percent more rainfall may be considered to reach the soil of the burned than the natural plot each year. (During the two years of burning annual interception losses of the natural plot totaled 2.2 and 3.1 inches.) Burning, on the other hand, greatly increased surface runoff. Thus while the natural plot showed no surface flow throughout the study the burned plot lost 6.8 inches in this way in 1936–37 and 23.8 inches in 1937–38. Evapo-transpiration was affected little by annual burning, averaging 13.0 inches per year on the natural plot and 12.2 inches on the burned. Percolation, calculated as the residuum, therefore varied roughly in inverse relation to surface runoff, being about 4 inches lower on the burned than the natural plot in 1936–37 and nearly 20 inches lower the next year.

Total water yield (combined surface runoff and percolation) was increased by burning. In 1936-37, this increase amounted to 2.7 inches and the next year, 4.4 inches. This does not mean, however, that the yield of usable water was greater from the burned than from the natural plot. Percolation constituted the entire yield of the natural plot. This type of yield provides water for prolonged ground-water flow which in turn contributes to more uniform and sustained stream flow. In contrast, surface runoff on the burned plot was one-fourth of its total yield the first year, and half its yield the next. This surface runoff caused soil erosion. As previously reported *(20, p. 27)* the burned plot lost more than 5 tons of soil per acre in 1936–37 and more than 85 tons per acre in 1937–38. Furthermore such surface flow is delivered quickly into stream channels where it contributes to increased peaks of flood flows, wasted water, and siltation of reservoirs. When the increased surface runoff and its attendant damages are considered the conclusion is reached that no improvement in water yield resulted from burning of the native brush on the North Fork plots.

Two years' recovery of the burned plot resulted in large decreases in surface runoff. Thus in the second year of recovery 40.8 inches of rain yielded 0.6 inch of surface runoff while 3 years earlier nearly the same quantity of rain yielded 6.8 inches of runoff. Recovery had little effect upon the quantity of evapo-transpiration. Increased evapo-transpiration was shown by this plot during the years 1938–39 and 1939–40, but since an increase was also shown by the natural plot it cannot be ascribed to the cessation of annual burning. Interception losses in the recovering vegetation were disregarded; thus water lost in this way was included in quantities assigned to evapo-transpiration and percolation. It can be assumed that interception losses were small, because of the low stature and sparse development of the vegetation during these 2 years. Hence total water yield (surface runoff and percolation) of the recovering and natural plots can be compared. During the first recovery year the burned plot yielded 0.5 inch less water than did the natural plot. The next year the total yield of the burned plot exceeded that of the natural plot by 2.1 inches, an amount equal to the measured interception loss on the natural plot.

Effect of Denudation

Although the bare plot at Nork Fork was first trenched in 1935 it was not maintained completely clear of vegetation and surface debris until the summer of 1936, a short time before the start of moisture sampling. Thus the quantity of water stored in the soil at the start of the study was affected by transpiration use of the vegetation prior to denudation. From this time on the soil surface was kept clean by frequent weeding and picking-off of leaves and other litter falling on the plot.

During the first 2 years (1936–37 and 1937–38) the soil-water storage characteristics of this plot (table 6) were closely similar to those of the burned plot. Each year this plot was wet through during the same storm as the burned plot, indicating that the rain required to wet the soil of both plots was not greatly different. In the same way, evapo-transpiration rates were not significantly different between the two plots during the wetting and percolation periods.

However, there were differences, some of which appear only in the last 2 years of the study. The summer drying curves for the 4 years of study (fig. 12) differed in important respects from those of the other 2 plots. First, they were gentler in slope, indicating lower average rates of water loss. Second, only in the drying period of one year (1936–37) did the storage of the entire soil drop below the wilting point, and then for only a short period compared with the other plots. In the other years (table 6) minimum storage remained at or above the wilting point. It was 4.1 inches, or an inch in excess of wilting-point storage at the end of the fourth year, 1939–40. The reason for the gradual rise in minimum storage through the years is not known, so the significance of this rise cannot be judged.

Study of the soil-water storage in the bare plot during the drying periods showed that evaporation rates decreased with depth as well as with time. This was also true on the natural and burned plots. But evaporation continued in the bare plot after the natural and burned plots had ceased to dry. Therefore, by the end of the drying period each year, water storage in the soil of the bare plot was reduced to amounts not greatly in excess of the minimum storage of the other two.

The disposition of precipitation on the bare plot follows, with minor variations, the pattern set by the burned plot during its 2 years of annual denudation. Interception loss was eliminated by complete removal of the vegetation cover. Surface runoff was considered to have been equal to that of the burned plot. Evidence of surface runoff was found in the erosion it caused; small gullies and erosion pavement developed on the plot. Evaporation from the bare soil averaged 11.6 inches per year, not much less than the average evapo-transpiration of 12.2 inches shown by the annually burned plot, or 13.0 inches shown by the natural plot, during these 2 years. Percolation for these 2 years averaged 11.5 inches less than that of the natural plot, and about 0.2 inch more than that of

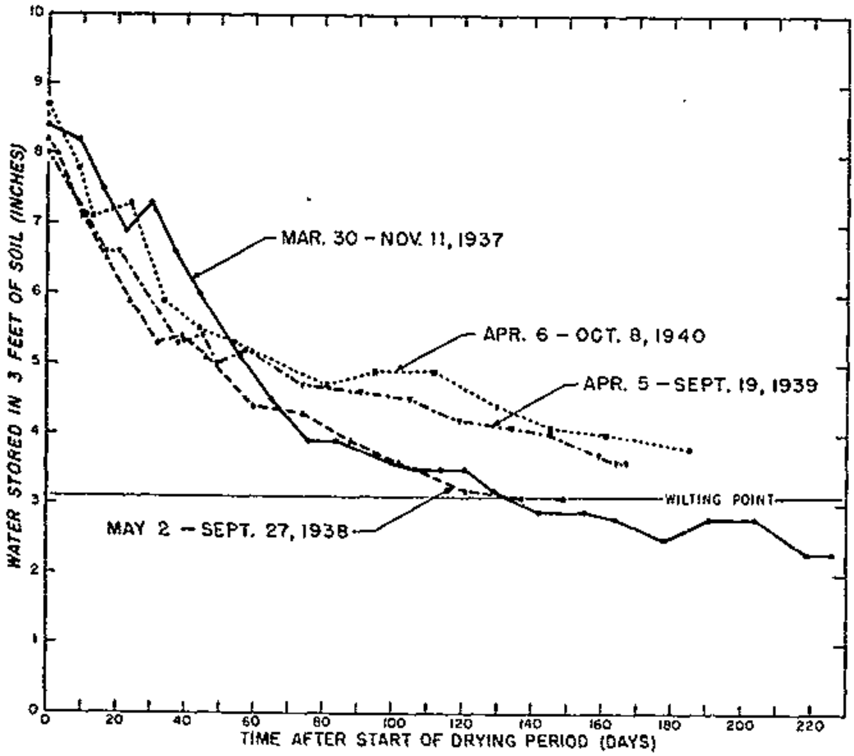

FIGURE 12.—Water storage in the soil of the North Fork bare plot during the drying periods, 1936-40.

the burned plot. Disposition of precipitation on the bare plot during the last 2 years followed the same general pattern except for variations caused by differences in annual rainfall.

In the foregoing analysis the quantities of evapo-transpiration and percolation are different from those which appear in Rowe's earlier study of these plots *(18, 20)*. These differences do not represent a contradiction, for qualitatively the results of the two analyses are identical. The differences result from an attempt to keep this analysis consistent and within the limits of the data available for all plots included in the study. The present analysis of the North Fork plots includes the years 1938–39 and 1939–40, which were not included in the earlier one, but does not include the previously reported years, 1934–35 and 1935–36. When these years were excluded it was found that in those remaining the depth of moisture sampling (soil depth to bedrock) was generally less than 4 feet. In the earlier analysis water-storage calculations had been based upon the 4-foot soil depth; but in the present analysis it was based upon the 3-foot depth reached in nearly all samplings. This change resulted, of course, in a reduction in evapo-

TABLE 6.—*Soil-water characteristics and rainfall disposition for the North Fork bare plot,*[1] *1936-40*

SOIL-WATER CHARACTERISTICS

Item	1936-37	1937-38	1938-39	1939-40	Average
Minimum storage (start of year)....inches..	2.4	2.5	3.1	3.5	[2] 3.1
Wilting point less minimum storage [3]....do..	.7	.6	0	−.4	[2] .0
Field-capacity storage....do..	8.5	8.7	8.5	8.5	8.6
Field capacity less minimum storage....do..	6.1	6.2	5.4	5.0	5.7
Rain to start percolation....do..	9.8	13.1	11.7	11.4	11.5
Mean evaporation rate:					
Wetting period....inches per day..	.009	.004	.038	.033	.021
Percolation period....do..	.082	.086	.087	.088	.070
Entire soil below wilting-point storage....days..	[4] 55	([5])	([5])	([5])	----------

RAINFALL DISPOSITION (INCHES)

Rainfall....	40.7	60.1	24.6	40.8	41.5
Interception loss....	0	0	0	0	0
Surface runoff [6]....	6.8	23.8	3.2	11.6	11.4
Rainfall entering soil....	33.9	36.3	21.4	29.2	30.2
Evaporation....	11.1	12.1	14.5	12.0	12.6
Percolation....	22.7	23.6	6.5	15.7	[7] 17.1

[1] Calculations based on 3-foot soil depth.
[2] Average includes minimum storage measurement of 4.1 inches at start of 1940-41 hydrologic year at which time sampling was discontinued.
[3] Wilting-point storage = 3.1 inches.
[4] Some transpiration use before complete denudation was effected in summer of 1936.
[5] Not below wilting point.
[6] Assumed same as burned plot in 1936-37 and 1937-38. Thereafter calculated for each storm on basis of infiltration rate (0.12 inch per hour) of burned plot prior to 1938.
[7] In addition, an average increment of 0.4 inch of rainfall per year was added to minimum storage.

transpiration and a corresponding increase in percolation. On the natural and burned plots the average difference in annual evapo-transpiration losses from the 3- and 4-foot deep soils was about 2.4 inches. On the bare plot the difference was only about half as great, owing to the lower loss from the 4-foot depth of this soil.

The second circumstance responsible for differences between the two analyses springs from the inclusion in the earlier analysis of quantities of water lost by evapo-transpiration during and between storms, when moisture sampling could not be used to detect such losses directly. The method used involved (1) determination of the relation between the evapo-transpiration rates during those interstorm periods when sampling could be relied upon and the corresponding rates of evaporation from a standard evaporation pan and (2) application of this relation to those periods during which sampling could provide no measurement. Lack of adequate storm and evaporation pan data made it impossible to calculate these quantities for some of the plots. In the interests of consistency, therefore, these quantities were not calculated for any of the plots in the present analysis. As a result the average annual evapo-transpiration quantities determined in the present analysis are from 0.5 inch lower (for the natural plot) to 0.9 to 1.5 inches lower (for the bare and annually burned plots) than those reported earlier. Calculated percolation, of course, is correspondingly higher.

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BASS LAKE PONDEROSA PINE

The soil of the Bass Lake plots averages 6 feet deep, about double that of the plots at North Fork; and it contains considerably more clay, which increases its wilting-point and field-capacity storage out of proportion to its increased depth. Increased soil-water storage, increased elevation, and a change from brush to coniferous cover all contribute to differences in the cycle of soil-water storage, in rainfall disposition, and in the effects upon rainfall disposition of burning and denudation.

The soil-water storage cycle of the natural plot at Bass Lake for a typical year (figs. 13 and 14) corresponds to that at North Fork (figs. 8 and 9). Such differences as appear are the result primarily of the larger quantities of water storage involved in the

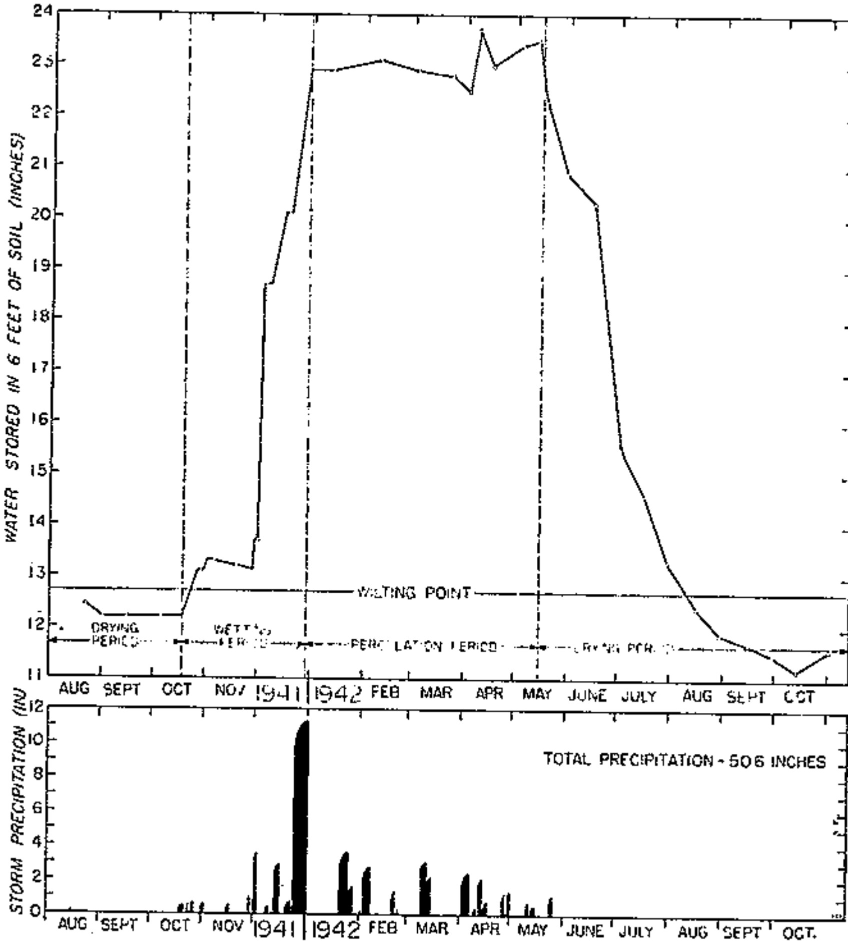

FIGURE 13.—Seasonal variations in storage of water in the soil of the Bass Lake natural plot, 1941-42.

Bass Lake cycles. Minimum storage (table 7) averaged 12.2 inches through the 5 years of record, and showed some increase during this time. The cause of this increase is not known, although it may possibly be associated with small changes in soil conditions encountered as different parts of the plot were sampled. The wilting-point storage of 12.7 inches is considered to represent the average wilting point of the whole plot. Therefore 0.5 inch represents the average amount by which this soil was depleted below the wilting point each year. Thus, although the Bass Lake soil generally dried below the wilting point, it did not dry as completely as the North Fork soil. The lower evaporation loss is probably contributed to by three conditions: The finer texture of the Bass Lake soil, which suggests lower permeability to water vapor; its greater depth, which requires a longer average path of travel before water vapor can leave the soil surface; and it deeper litter cover, which increases insulation.

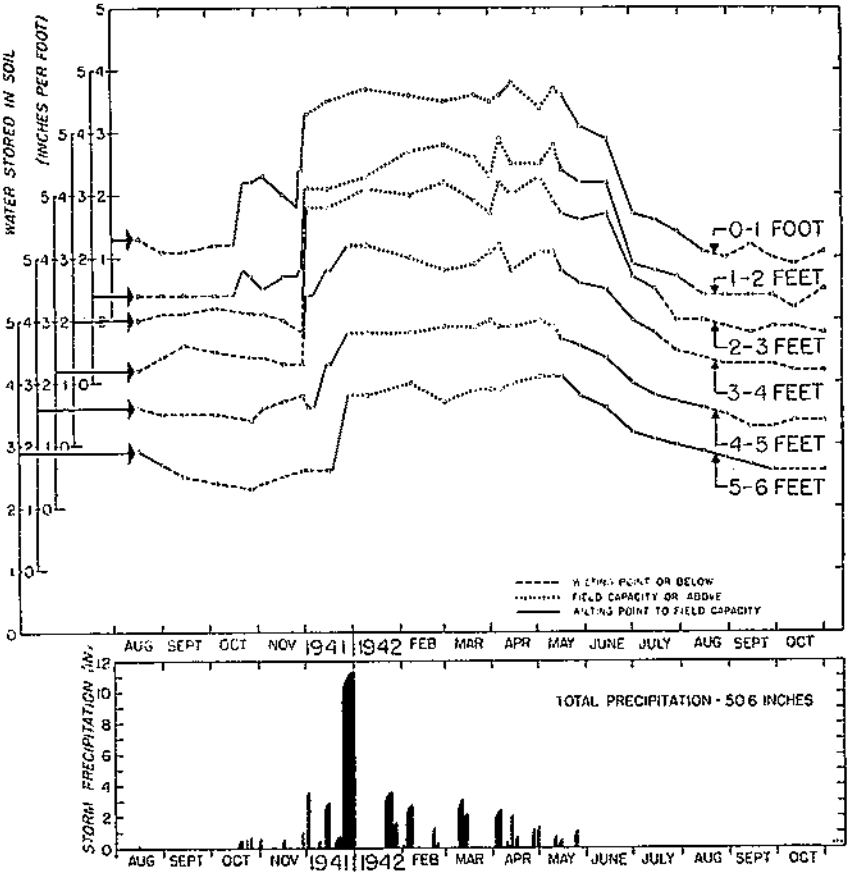

FIGURE 14.—Seasonal variations in the storage of water in foot-by-foot soil depths of the Bass Lake natural plot, 1941-42.

TABLE 7.—*Soil-water characteristics and rainfall disposition for the Bass Lake natural plot,*[1] *1940-45*

SOIL-WATER CHARACTERISTICS

Item	1940–41	1941–42	1942–43	1943–44	1944–45	Average
Minimum storage (start of year) .... inches	11.5	12.2	11.9	13.3	13.0	[2] 12.2
Wilting point less minimum storage [3] .... do.	1.2	.5	.8	−.6	−.3	[2] .5
Field-capacity storage .... do.	23.0	23.0	23.0	24.0	23.8	23.4
Field capacity less minimum storage .... do.	11.5	10.8	11.1	10.7	10.8	11.0
Rain to start percolation .... do.	17.5	[4] 14.8	16.8	[4] 18.4	12.2	15.9
Mean evapo-transpiration rate:						
Wetting period .... inches per day	.066	.013	.094	.035	(6)	.042
Percolation period .... do.	(5)	.005	(5)	(5)	.033	.008
Entire soil below wilting-point storage .. days	33	46	(6)	(6)	(6)	16

RAINFALL DISPOSITION (INCHES)

Rainfall	58.6	50.6	50.9	38.5	49.6	49.6
Interception loss	7.2	6.4	5.6	4.8	5.3	5.9
Surface runoff	0	.1	0	.4	.3	.2
Rainfall entering soil	51.4	44.1	45.3	33.3	44.0	43.6
Evapo-transpiration	14.8	14.8	17.8	19.6	17.5	16.9
Percolation	35.9	29.6	26.1	14.0	28.0	26.7

[1] Calculations based on 6-foot soil depth.
[2] Average includes minimum storage measurement of 11.5 inches at start of 1945–46 hydrologic year.
[3] Wilting-point storage = 12.7 inches.
[4] Precipitation required to start percolation in 1941–42 and 1943–44 included about 0.6 inch held as unmelted snow.
[5] Losses may have occurred but were too small to be detected by sampling method used.
[6] Sixth foot above wilting point.

The mean field-capacity storage of 23.4 inches shows that at least 10.7 inches of water must be added to this soil before percolation can start. Actually, between 12.2 inches and 18.4 inches of rain were required to wet this soil to field capacity, the quantities depending upon the size and distribution of rains and the amount of evapo-transpiration between storms of the wetting period.

Evapo-transpiration rates were greater during the wetting period than during the subsequent percolation period. In fact, evapo-transpiration shown by moisture sampling during the percolation period was negligible on all the Bass Lake plots during the years studied. This is quite different from the situation at North Fork, for there evapo-transpiration rates were invariably greater during the percolation than during the wetting period. This difference was probably largely an effect of deeper litter, lower temperatures, and the greater amount of precipitation occurring as snow at Bass Lake.

Finally, another difference was in the drying of the natural plot (fig. 15). In two of the years studied, wilting-point storage was reached about 3½ months after the start of the drying period, a month longer than at North Fork. In the other years wilting-point storage was not reached before the next rainy season started. It is apparent (table 7) that soil-water storage at Bass Lake did not remain below the wilting point for lengths of time nearly as great as under natural vegetation at North Fork.

Rainfall disposition varied only in degree from that of the natural plot at North Fork. Interception loss accounted for roughly

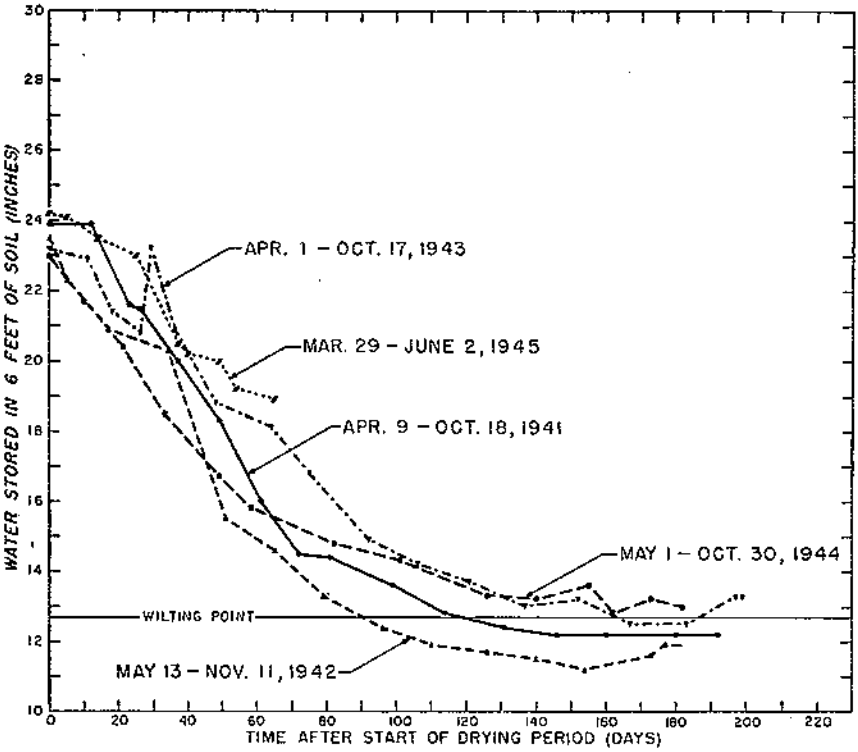

FIGURE 15.—Water storage in the soil of the Bass Lake natural plot during the drying periods of 1941 through 1945. Record of soil drying during the latter part of 1944-45 season is incomplete. Soil-water storage in the 0-6 foot depth at end of the season was approximately 1.2 inches below wilting point.

12 percent of the annual precipitation as compared with 5 percent at North Fork. A very small, yet measurable, part of the rain was sometimes lost as surface runoff, even under the undisturbed forest cover. Yearly evapo-transpiration varied from 14.8 inches to 19.6 inches, most of it taking place during the summer drying period. At North Fork yearly evapo-transpiration was between 11.7 and 15.7 inches from soil half as deep as that at Bass Lake, and a much greater portion of this annual loss took place during each year's wetting and percolation periods. Percolation at Bass Lake ranged from 14.0 inches with annual rainfall of 38.5 inches to 35.9 inches with rainfall of 58.6 inches. At North Fork, by comparison, 40.7 inches of rain produced 26.8 inches of percolation, while 60.1 inches produced 42.5 inches of percolation. The difference between the natural plots in the two localities is largely the result of greater interception loss on the Bass Lake plot, and the higher available water-storage capacity of the soil, which resulted in the greater evapo-transpiration loss each year.

Effect of Burning

The soil-water cycle of the burned plot differed from that of the natural plot principally in relation to soil differences. Minimum storage (table 8) averaged 11.5 inches, 0.9 inch less than wilting-point storage. Thus, the wilting-point deficit of this plot was somewhat greater, on the average, than that of the natural plot. The field-capacity deficit was greater and, as was anticipated, so was the rain required each year to initiate percolation (21 to 32 inches).

Evapo-transpiration rates were not significantly different between the two plots during the rainy season, and in the burned plot as in the natural plot the amount of evapo-transpiration measured during the percolation period was small.

Summer drying on the burned plot (fig. 16) was more rapid than on the natural plot. Thus, the burned plot lost nearly 4 inches more water than the natural plot in drying from field capacity to wilting point, and it reached wilting-point storage at an earlier date. A combination of 3 circumstances was responsible for this. First, the burned plot held a greater quantity of water available for transpiration than did the natural plot. Second, burning consumed the litter but not the tree cover so that transpiration was unaffected. Third, loss of the insulating litter cover provided opportunity for greater evaporation from the soil. That such an increase in evaporation did result is suggested by differences in evapo-transpiration losses during early summer at two depths in the burned and natural plots. Within the top foot of soil on the

TABLE 8.—*Soil-water characteristics and rainfall disposition for the Bass Lake burned plot,[1] 1940-45*

SOIL-WATER CHARACTERISTICS

Item	1940-41	1941-42	1942-43	1943-44	1944-45	Average
Minimum storage (start of year) ...inches	12.4	11.9	12.3	11.3	11.0	[2]11.5
Wilting point less minimum storage [3] ...do	0	.5	.1	1.1	1.4	[2].9
Field-capacity storage ...do	26.7	27.0	26.5	27.0	26.0	26.6
Field capacity less minimum storage ...do	14.3	15.1	14.2	15.7	15.0	14.9
Rain to start percolation ...do	22.1	[4]21.3	29.2	[4]31.7	[4]30.7	27.0
Mean evapo-transpiration rate:						
Wetting period ...inches per day	.034	.039	.025	.040	.039	.035
Percolation period ...do	([5])	([5])	([5])	([5])	([5])	([5])
Entire soil below wilting-point storage ...days	([6])	74	63	45	28	42

RAINFALL DISPOSITION (INCHES)

Item	1940-41	1941-42	1942-43	1943-44	1944-45	Average
Rainfall	58.6	50.6	50.9	38.5	49.6	49.6
Interception loss	7.2	6.4	5.6	4.8	5.3	5.9
Surface runoff	6.4	5.3	13.3	6.1	15.5	9.3
Rainfall entering soil	45.0	38.9	32.0	27.6	28.8	34.5
Evapo-transpiration	17.6	18.5	18.8	23.9	22.4	20.2
Percolation	27.9	20.0	14.2	4.0	7.5	14.7

[1] Calculations based on 6-foot soil depth.
[2] Average includes minimum storage measurement of 9.9 inches at start of 1945-46 hydrologic year.
[3] Wilting-point storage = 12.4 inches.
[4] Precipitation required to start percolation in 1941-42 included about 1.4 inches of unmelted snow, in 1943-44 about 4.0 inches, and in 1944-45 about 0.1 inch.
[5] Losses may have occurred but were too small to be detected by sampling method used.
[6] Sixth foot above wilting point.

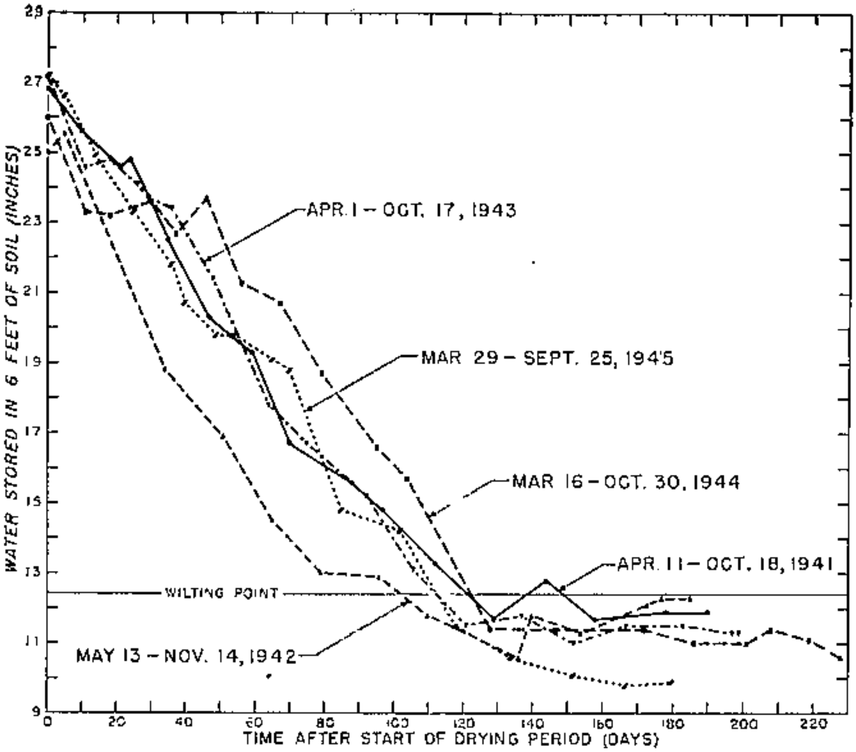

FIGURE 16.—Water storage in the soil of the Bass Lake burned plot during the drying periods of 1941 through 1945.

burned plot, evapo-transpiration losses at this time were between 1½ and 2 times as great as those in the natural plot. Within the sixth foot, where evaporation would be little affected by the litter cover, there was no significant difference in loss rates between the plots.

Rainfall disposition followed in general the pattern set by the burned plot at North Fork. Such differences as occurred were due to differences in burning method and in soil characteristics at the two locations.

Evapo-transpiration on the burned plot in ponderosa pine ranged from 17.6 inches to 23.9 inches per year. The average yearly loss was 3.3 inches more than that of the ponderosa pine natural plot, but the difference in available water storage could account for this.

Because only very small trees and material on the ground were consumed in the fires, interception was considered not to have been changed by burning. Surface runoff, however, was increased by burning. Thus, for years during which runoff on the natural plot did not exceed 0.4 inch, runoff on the burned plot ranged between 5.3 and 15.5 inches. Surface runoff on the natural plot caused no measurable amounts of soil erosion, but that on the burned plot washed away the topsoil at an average rate of more than 4 tons per acre per year. Water entry into the soil was reduced by the amount of runoff and so, correspondingly, was percolation through the soil. Annual percolation ranged from 14.0 to 35.9 inches on the natural plot, and from 4.0 to 27.9 inches on the burned plot.

Part of the difference in percolation between plots can be attributed to the greater field-capacity deficit which must be satisfied each year on the burned plot before percolation can take place. But the difference is greater than can be accounted for in this way. Percolation is, without question, more strongly influenced by increased surface runoff than by any other hydrologic change resulting from annual burnings of the litter cover.

Effect of Denudation

The soil-water-storage characteristics of the bare plot at Bass Lake are midway between those of the burned and natural plots. Field-capacity storage is close to that of the burned plot, while wilting-point storage is greater than in either of the other two (table 9). As a result the available water storage of this plot (field capacity less wilting point) lies between that of the other two. Although this plot was kept completely free of surface vege-

TABLE 9.—*Soil-water characteristics and rainfall disposition for the Bass Lake bare plot,[1] 1940-45*

SOIL-WATER CHARACTERISTICS [2]

Item	1940-41	1941-42	1942-43	1943-44 [3]	1944-45 [3]	Average
Minimum storage (start of year) [4] ... inches	13.2	18.4	18.4	17.0	15.0	[5] 17.9
Wilting point less minimum storage [6] ... do	.8	−4.4	−4.4	−3.0	−1.0	[5] −3.9
Field-capacity storage ... do	27.0	26.6	26.5	26.3	24.6	[5] 26.5
Field capacity less minimum storage ... do	13.8	8.2	8.1	9.3	9.6	[5] 8.5
Rain to start percolation ... do	[7] 18.6	[7, 8] 14.7	[7] 23.7	[8] 16.3	[8] 28.3	[5] 18.2
Mean evapo-transpiration rate:						
Wetting period ... inches per day	.044	([9])	.013	.022	.020	[10] .019
Percolation period ... do	([9])	.022	([9])	([9])	([9])	[10] .007

RAINFALL DISPOSITION (INCHES)

Item	1940-41	1941-42	1942-43	1943-44	1944-45	Average
Rainfall	58.6	50.6	50.9	38.5	49.6	[10] 53.4
Interception loss	0	0	0	0	0	0
Surface runoff	([7])	([7])	([7])	13.2	24.9	------
Rainfall entering soil	------	------	------	25.3	24.7	------
Evaporation [11]	12.0	11.2	11.0	10.3	17.0	[10] 11.4
Percolation + runoff	41.4	39.4	41.3	24.2	34.7	[10] 40.7
Percolation	------	------	------	11.0	9.8	------

[1] Calculations based on 6-foot soil depth.
[2] In 1943-44 the first foot, and in 1944-45 the first 5 feet of soil dropped below wilting point.
[3] Roots active.
[4] Minimum storage for 1940-41 measured at time of trenching. Minimum storage at start of year 1945-46 was 12.9 inches.
[5] Average based only on those seasons 1941-42, 1942-43, and 1943-44, in which water relations were unaffected by vegetation activity within the plot.
[6] Wilting-point storage = 14.0 inches.
[7] Runoff not measured.
[8] Precipitation required to start percolation in 1941-42 included about 0.7 inch unmelted snow, in 1943-44 about 0.2 inch, and in 1944-45 about 0.1 inch.
[9] Losses may have occurred but were too small to be detected by sampling method used.
[10] Average based only on seasons 1940-41, 1941-42, and 1942-43.
[11] The 1943-44 and 1944-45 seasons include transpiration use by invading roots.

tation, its soil-water relations, and more particularly its evaporation rates, are probably affected by the shading of trees which surround the plot area.

The plot was trenched and walled up in the fall of 1940, at which time its minimum water storage was 13.2 inches, 0.8 inch less than wilting-point storage (table 9). The soil mass had supported plant gowth until the date of trenching. Because of this the minimum storage in the fall of 1940 was in close agreement with that of the other plots, when wilting-point differences are considered. For the next 3 years minimum storage remained reasonably constant at values between 3.0 and 4.4 inches in excess of the wilting point. The trend of the summer drying curves for these years (fig. 17) shows that evaporation rates were much lower on this plot than were the combined evapo-transpiration rates on the others. Study of water storage in individual soil layers showed that during the summer the upper 3 feet of the soil dried more rapidly and more completely than did the soil beneath.

During the last 2 years of the study there were significant drops in minimum storage, increases in rates of summer water loss, and accompanying increases in annual evaporative water losses. In

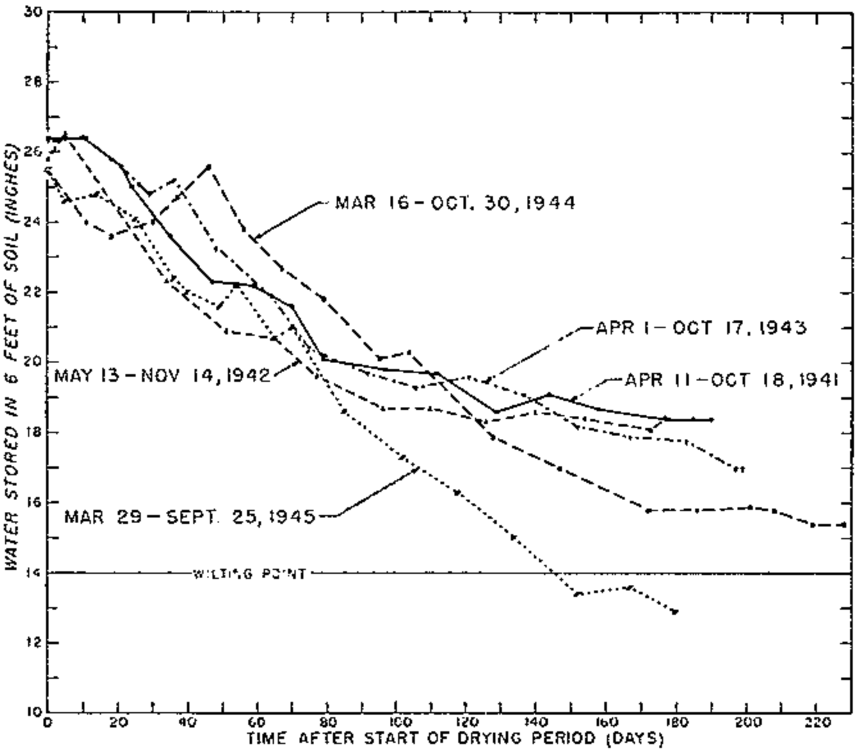

FIGURE 17.—Water storage in the soil of the Bass Lake bare plot during the drying periods of 1941 through 1945.

1945 the soil dried to a minimum storage of 12.9 inches, about the same as in 1940 before trenching. This was 5.5 inches lower than the minimum reached in 1941 and 1942.

The decrease in minimum storage suggested that sometime after the fall of 1943 plant roots had invaded the bare plot. Before then all roots entering the plot had been cut back frequently. An examination in 1948 proved that roots had entered the plot; a trench dug to the top of the sheet-metal wall around half the plot unearthed 16 roots, which varied in diameter from ½ inch to 1½ inches at the point where they crossed the wall (fig. 18). Some of these roots came from trees 10 or more feet away. All of them grew upward along the wall and then over its top to invade the soil inside.

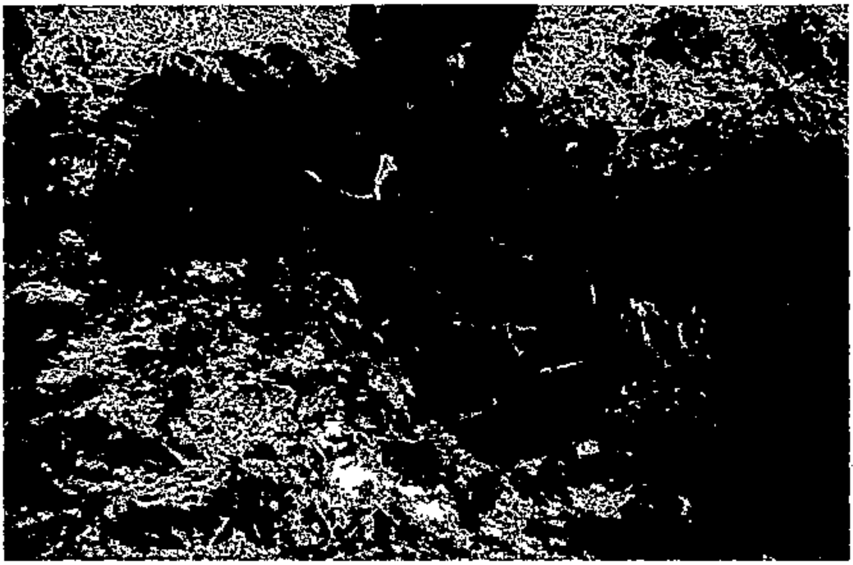

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FIGURE 18.—Some of the roots entering the bare plot at Bass Lake. The sheet-metal wall bounding the plot runs diagonally across the photograph. The large invading root grew directly to the side of the wall, turned up, grew along the top of the wall for a short distance, and then entered the plot. (Photographed in April 1948.)

Because of the root invasion, the bare plot could not be considered vegetation-free during the last 2 years of the study. For this reason average values of water storage and quantities of evaporation can only be calculated for the first 3 years (table 9). Minimum storage has already been discussed from this point of view. Field-capacity storage cannot be considered to have been influenced by root invasion. Annual evaporation averaged 11.1 inches on the bare plot, which is 6.9 inches less than the 3-year mean evapo-transpiration of the burned plot and 4.4 inches less than that of the natural plot.

Rainfall disposition was rather strikingly affected by denudation. If all rainfall reaching the soil were to enter the bare plot each year, then the lower field-capacity deficit of this plot (due to lesser evaporation loss) would result in earlier percolation, and more percolation, than would be found on either the burned or natural plot. Furthermore, because interception loss was eliminated, some 12 percent more rain would be delivered to this soil each year. Actually when tables 7, 8, and 9 are studied for 1943–44 and 1944–45, during which time runoff was measured on the bare plot, it is found that the plot yielded more percolation than the burned plot, but much less than the natural plot. During these years surface runoff accounted for 13.2 and 24.9 inches of the annual rainfall on the bare plot, 6.1 and 15.5 inches on the burned plot, and 0.4 and 0.3 inch on the natural plot. Measurements of soil erosion made on a small segment of the bare plot during these 2 years indicated that erosion rates were also much greater than on the burned plot. If the storm-by-storm runoff relations between the bare plot and the other two were the same during the first 3 years as during the last two, then the quantity of percolation would still fall between the quantities shown by the other plots.

SAN DIMAS CHAPARRAL

The soil of the San Dimas plots is 5 feet deep, thus placing it between the soils at North Fork and Bass Lake. In field-capacity and wilting-point storage it likewise fell between the other two, when considered either foot-by-foot or by total soil depth (table 2). Some differences in rainfall disposition would be anticipated between the San Dimas plots and the others because of differences in soil, vegetation, and location.

The four San Dimas plots differ among themselves primarily in the available water storage of their soils. The mixed chaparral and ceanothus plots have a field-capacity storage about 2 inches less than the chamise and bare plots, while the wilting-point storage of all four shows very little variation. It is therefore possible to discuss in some detail the soil-water cycle and rainfall disposition of but one of these plots in order that comparisons can be made between the natural plots here, at Bass Lake, and at North Fork. Likewise, discussion of one plot can serve as a basis of comparison for the other San Dimas plots. The mixed chaparral plot has been selected for this purpose.

Mixed Chaparral

The soil-water cycle of this plot (figs. 19 and 20) followed, with minor variations, the trends shown by the natural plots elsewhere. Minimum storage ranged from 3.6 inches to 4.7 inches, averaging 1.3 inches below wilting-point storage (table 10). The rain required to wet the soil to field-capacity storage was considerably greater than the difference between minimum and field-capacity storage and varied from year to year. This variation was due to differences in frequency and size of storms. Evapo-transpiration

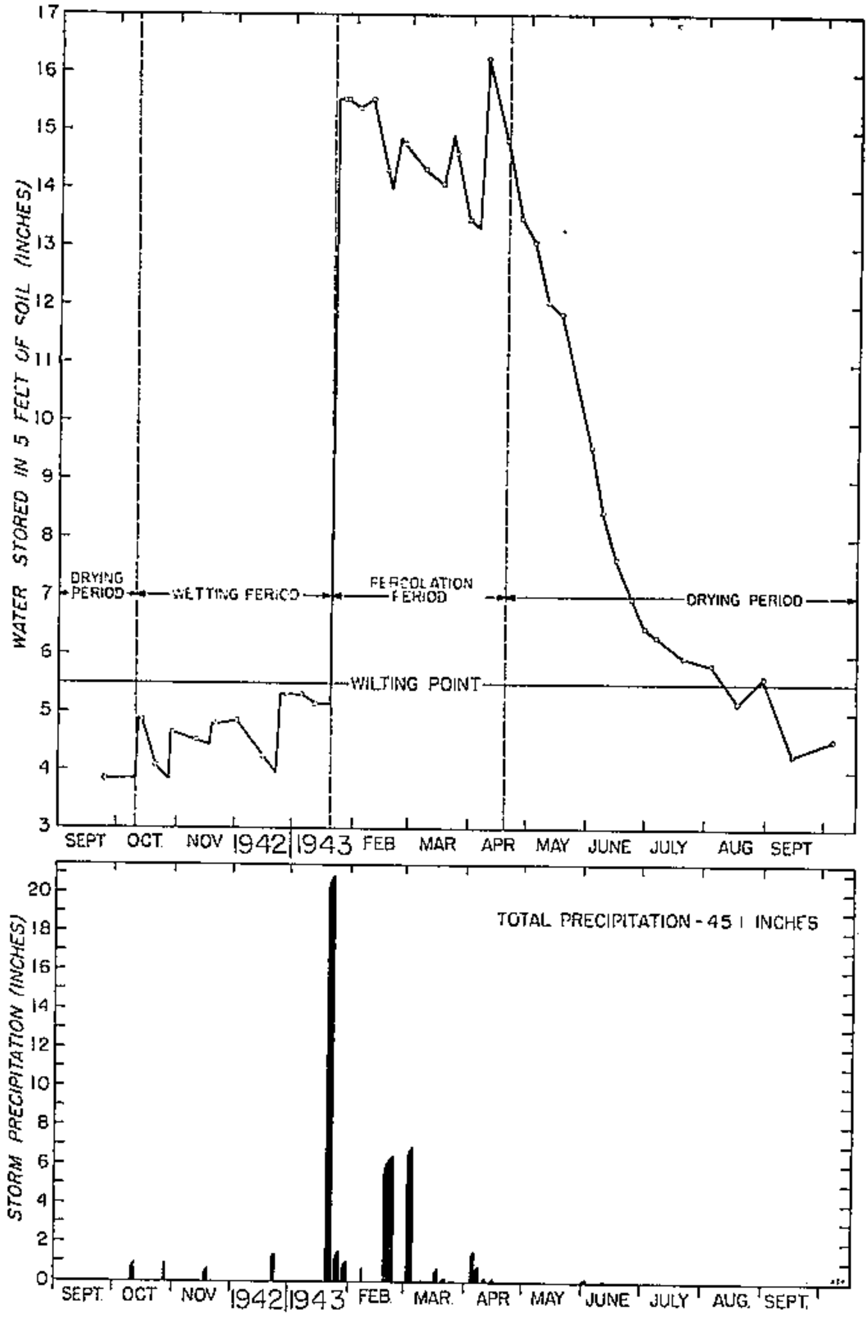

FIGURE 19.—Seasonal variations in storage of water in the soil of the San Dimas mixed chaparral plot, 1942-43.

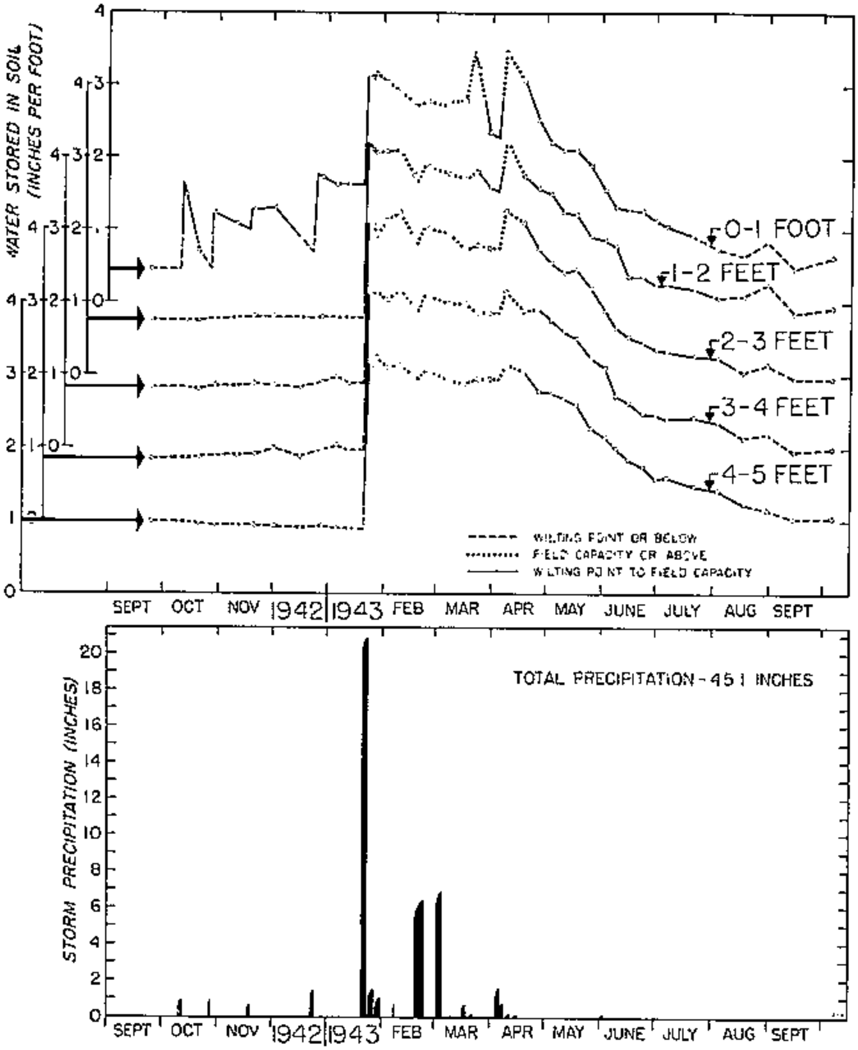

FIGURE 20.—Seasonal variations in the storage of water in foot-by-foot soil depths of the San Dimas mixed chaparral plot, 1942-43.

rates averaged close to 0.06 inch per day during the wetting period and nearly 0.03 inch per day through the percolation period, indicating fair agreement with rates found at Bass Lake and North Fork. Summer drying (fig. 21) followed the same trend as it did on the North Fork and Bass Lake natural plots, i.e., a gradual decrease in rate until wilting-point storage was reached (in about 4 months), and a much smaller and slower loss thereafter. Here, as at North Fork, the soil may be below wilting-point storage at all depths for long periods during the summer and fall.

TABLE 10.—*Soil-water characteristics and rainfall disposition for the San Dimas mixed chaparral plot,[1] 1940-43*

SOIL-WATER CHARACTERISTICS

Item	1940-41	1941-42	1942-43	Average
Minimum storage (start of year) ....inches	3.6	4.7	3.9	[2] 4.2
Wilting point less minimum storage [3] ....do	1.9	.8	1.6	[2] 1.3
Field-capacity storage ....do	14.5	([4])	14.5	[6] 14.5
Field capacity less minimum storage ....do	10.9	([4])	10.6	[6] 10.8
Rain to start percolation ....do	22.9	([4])	14.7	[6] 18.8
Mean evapo-transpiration rate:				
Wetting period ....inches per day	.087	.072	.019	.059
Percolation period ....do	([5])	([4])	.058	[6] .029
Entire soil below wilting-point storage ....days	10	118	47	58

RAINFALL DISPOSITION (INCHES)

Item	1940-41	1941-42	1942-43	Average
Rainfall	47.8	16.8	45.1	[6] 46.4
Interception loss	3.9	2.4	3.3	[6] 3.6
Surface runoff	0	0	0	0
Rainfall entering soil	43.9	14.4	41.8	[6] 42.8
Evapo-transpiration	19.0	15.2	17.1	[6] 18.0
Percolation	23.8	0	24.0	[6] 23.9

[1] Calculations based on 5-foot soil depth.
[2] Average includes minimum storage measurement of 4.6 inches at start of 1943-44 hydrologic year.
[3] Wilting-point storage = 5.5 inches.
[4] Insufficient rain to raise soil to field capacity.
[5] Losses may have occurred but were too small to be detected by sampling method used.
[6] Two-year average; 1941-42 not included because rain was not sufficient to wet through soil.

The disposition of rainfall is particularly interesting in the years during which this plot was studied. In the first and third year, precipitation was very nearly the same: 47.8 inches and 45.1 inches, respectively (table 10). In 1940-41, the first year, rains of the wetting period occurred in such a way that the soil was alternately wetted and dried several times before percolation was produced. In 1942-43 the few small storms at the start of the rainy season caused little net increase in soil-water storage, but on January 21-23, 1943, a single storm brought more than 20 inches of rain, wet the entire soil, and produced percolation. Because of this quick recharge of field-capacity storage, a smaller amount of rain was required to start percolation in the third year. In the second year, 1941-42, rain was not sufficient at any time to produce percolation or to increase water storage appreciably below the 2-foot soil depth. As would be expected, all rain falling on the plot that year was lost to the atmosphere as interception and evapo-transpiration.

Interception averaged about 9 percent of the annual precipitation. Interception losses thus fall between those at North Fork and Bass Lake. Runoff was negligible, a finding in agreement with results of both the other natural plots. Annual evapo-transpiration averaged 18 inches in the years during which rainfall was sufficient to wet the entire soil mantle. This loss is somewhat greater than that shown generally by the North Fork and Bass Lake natural plots. The difference can probably be attributed to the shallower soil at North Fork (that is, there was less stored water to be lost), and to the generally lower evapo-transpiration rates at Bass Lake.

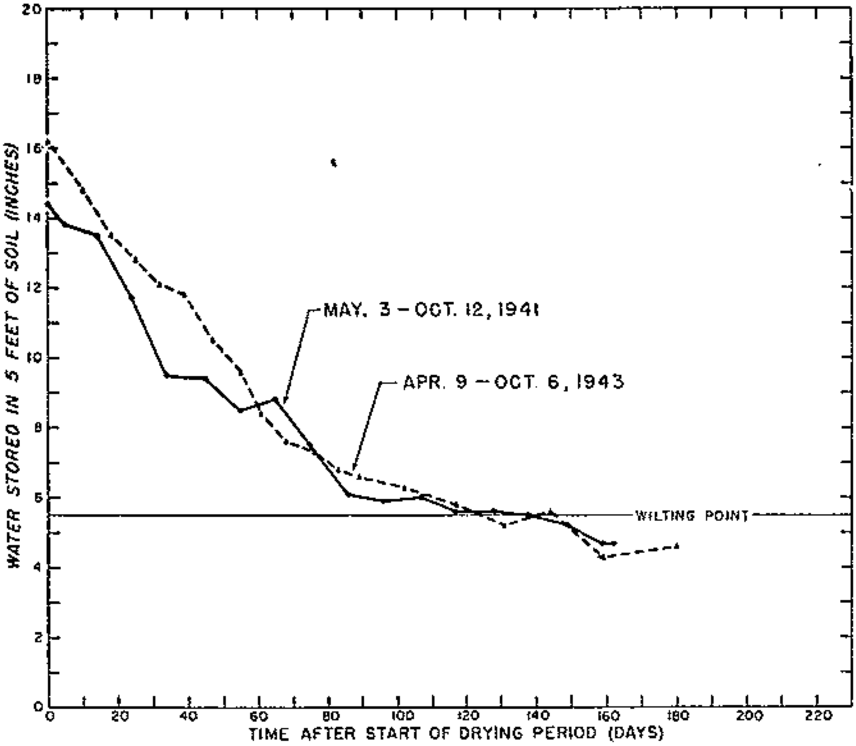

FIGURE 21.—Water storage in the soil of the San Dimas mixed chaparral plot during the drying periods of 1941 and 1943.

Percolation, being a function primarily of the amount of annual rainfall, and secondarily of the spacing of storms and quantity of rainfall per storm, was about the same in 1940–41 and 1942–43. For similar amounts of precipitation, however, percolation was less in the mixed chaparral than in either the North Fork or Bass Lake natural plots.

Pure Stands of Chaparral

The ceanothus and chamise plots, situated near Tanbark Flat in nearly pure stands of 2 of the species found on the mixed chaparral plot, exhibit closely similar characteristics of soil-water storage (tables 11 and 12). Furthermore, these characteristics are virtually identical to those of the mixed chaparral plot. Thus in the ceanothus plot minimum storage averaged 1.4 inches less than wilting-point storage (table 11), in the chamise plot 1.3 inches less (table 12), and in the mixed chaparral plot 1.3 inches less. Evapo-transpiration rates are virtually the same in the ceanothus and chamise plots; these rates are not significantly different from those of the mixed chaparral. Some minor differences between plots are found in the amount of rain required to start percolation, and the time during which storage was below the wilting point.

TABLE 11.—*Soil-water characteristics and rainfall disposition for the San Dimas ceanothus plot,*[1] *1940-43*

SOIL-WATER CHARACTERISTICS

Item	1940-41	1941-42	1942-43	Average
Minimum storage (start of year) ... inches	3.9	4.0	3.7	[2] 3.9
Wilting point less minimum storage [3] ... do	1.4	1.3	1.6	[2] 1.4
Field-capacity storage ... do	15.5	(4)	15.0	[6] 15.2
Field capacity less minimum storage ... do	11.6	(4)	11.3	[6] 11.4
Rain to start percolation ... do	20.1	(4)	15.6	[6] 17.8
Mean evapo-transpiration rate:				
Wetting period ... inches per day	.077	.060	.034	.059
Percolation period ... do	(5)	(4)	.070	[6] .040
Entire soil below wilting-point storage ... days	52	144	64	87

RAINFALL DISPOSITION (INCHES)

Item	1940-41	1941-42	1942-43	Average
Rainfall	47.8	16.8	45.1	[6] 46.4
Interception loss [7]	3.9	2.4	3.3	[6] 3.6
Surface runoff [7]	0	0	0	0
Rainfall entering soil	43.9	14.4	41.8	[6] 42.8
Evapo-transpiration	17.6	14.7	19.3	[6] 18.4
Percolation	26.2	0	22.3	[6] 24.2

[1] Calculations based on 5-foot soil depth.
[2] Average includes minimum storage measurement of 3.9 inches at start of 1943-44 hydrologic year.
[3] Wilting-point storage = 5.3 inches.
[4] Insufficient rain to raise soil to field capacity.
[5] Losses may have occurred but were too small to be detected by sampling method used.
[6] Two-year average; 1941-42 not included because rain was not sufficient to wet through soil.
[7] Not measured. Assumed equal to that on the mixed chaparral plot.

TABLE 12.—*Soil-water characteristics and rainfall disposition for the San Dimas chamise plot,*[1] *1940-43*

SOIL-WATER CHARACTERISTICS

Item	1940-41	1941-42	1942-43	Average [2]
Minimum storage (start of year) ... inches	4.9	5.3	4.8	5.0
Wilting point less minimum storage [3] ... do	1.4	1.0	1.5	1.3
Field-capacity storage ... do	17.5	...	17.3	17.4
Field capacity less minimum storage ... do	12.6	...	12.5	12.6
Rain to start percolation ... do	22.0	...	16.0	19.0
Mean evapo-transpiration rate:				
Wetting period ... inches per day	.087	...	.035	.061
Percolation period ... do	(4)	...	.060	.030
Entire soil below wilting-point storage ... days	70	...	17	44

RAINFALL DISPOSITION (INCHES)

Item	1940-41	1941-42	1942-43	Average [2]
Rainfall	47.8	...	45.1	46.4
Interception loss [5]	3.9	...	3.3	3.6
Surface runoff [5]	0	...	0	0
Rainfall entering soil	43.9	...	41.8	42.8
Evapo-transpiration	19.7	...	18.3	19.0
Percolation	23.8	...	23.3	23.6

[1] Calculations based on 5-foot soil depth.
[2] Two-year average except for first two items which include a minimum storage measurement of 5.0 inches at start of 1943-44 hydrologic year.
[3] Wilting-point storage = 6.3 inches.
[4] Losses may have occurred but were too small to be detected by sampling method used.
[5] Not measured. Assumed equal to that of the mixed chaparral plot.

They can be ascribed to small differences in soil characteristics between the plots. Summer drying in both pure stands (figs. 22 and 23) is like the drying trend of the mixed chaparral plot.

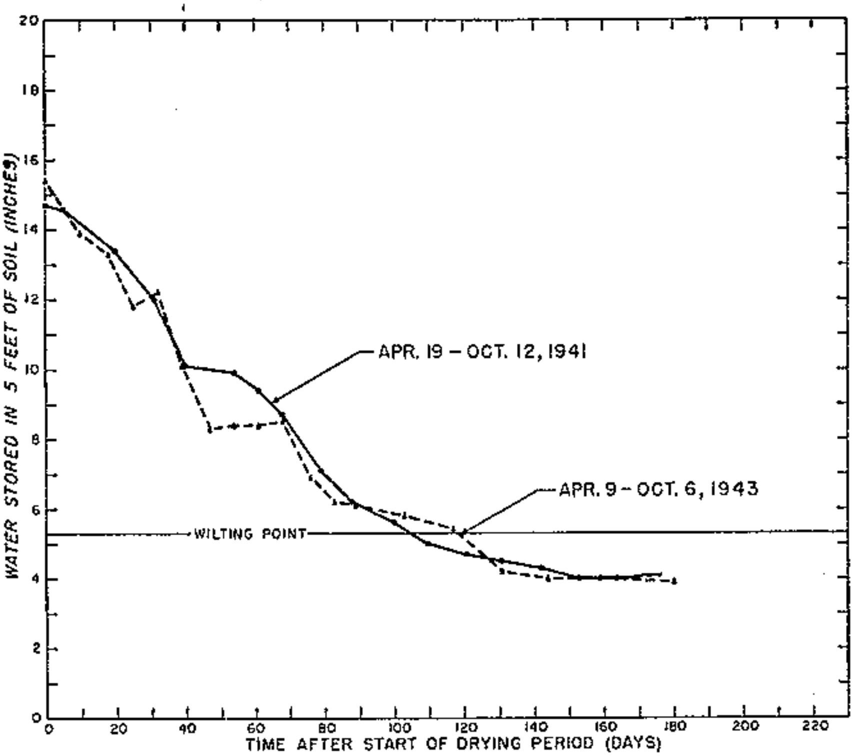

FIGURE 22.—Water storage in the soil of the San Dimas ceanothus plot during the summer drying periods of 1941 and 1943.

Because the water storage characteristics of these plots were so much the same, and because interception losses and runoff are considered to be identical, the characteristics of rainfall disposition (tables 11 and 12) were very similar in the ceanothus and chamise plots, and closely resembled those of the mixed chaparral plot. The only point which requires mention in this connection is the evapo-transpiration loss in the 2 years when sufficient rain fell to raise all the plots to field capacity: The mixed chaparral plot lost an average of 18.0 inches of water, the ceanothus plot 18.4 inches, and the chamise plot, holding somewhat more water available to evapo-transpiration than either of the other two, lost 19.0 inches. Thus all these plots are found to be very similar hydrologically, despite their differences in plant cover.

Effect of Denudation

No record of surface runoff is available for the San Dimas bare plot. Hence runoff and percolation are combined in the present analysis. In terms of soil characteristics, this plot closely resembles the adjacent chamise plot, and it can best be considered in relation to that plot.

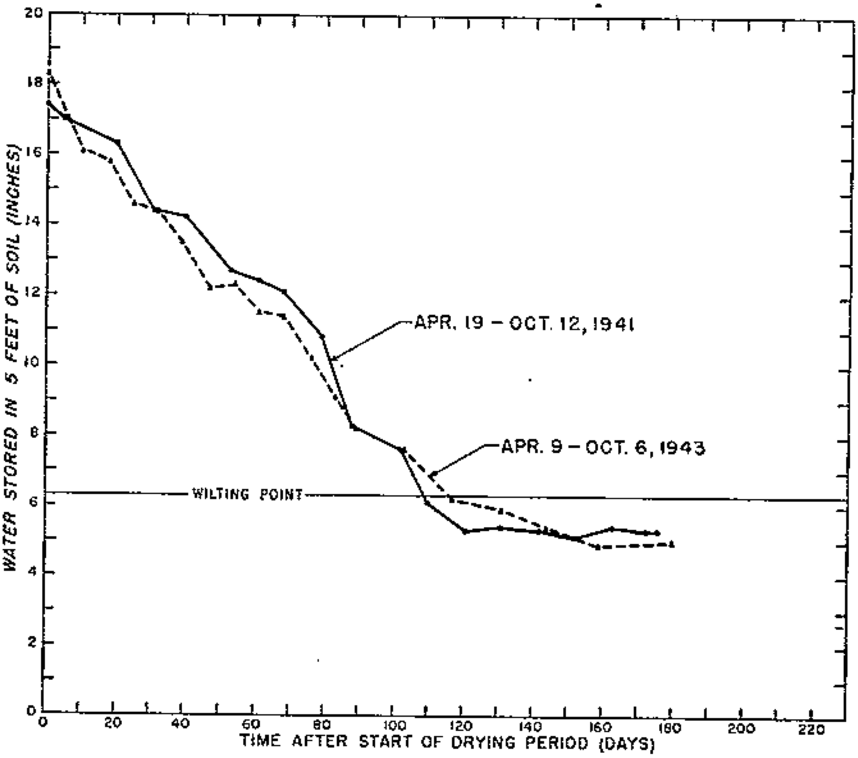

FIGURE 23.—Water storage in the soil of the San Dimas chamise plot during the summer drying periods of 1941 and 1943.

In the fall of 1940 when the bare plot was first trenched, soil-water storage had been depleted 1.9 inches below the wilting point (table 13). This agrees well with the 1.4-inch wilting-point deficit of the chamise plot, as well as the others of the San Dimas group. The bare plot also dropped below wilting-point storage in the low rainfall year 1941–42. But in the other years (1940–41 and 1942–43) its minimum storage was higher than the wilting point by from 0.3 inch to 1.2 inches. Summer evaporation losses (fig. 24) occurred at a relatively uniform rate until near the end of the drying period when soil-water storage approached the wilting point. The soil dried slightly more rapidly and more completely in the upper than in the lower layers. During the wetting period rates of soil-water loss were somewhat lower on the bare plot than on the chamise plot, but during the percolation period, there was no significant difference.

Rainfall disposition (table 13) was definitely affected by denudation. Interception loss disappeared and the combined runoff and percolation exceeded percolation from the adjacent chamise plot by 5.6 inches in 1940–41 and 3.0 inches in 1942–43. Although observations of surface washing and soil erosion on the bare plot showed that some water left it as surface runoff, no estimate of

TABLE 13.—*Soil-water characteristics and rainfall disposition for the San Dimas bare plot,[1] 1940-43*

SOIL-WATER CHARACTERISTICS

Item	1940-41	1941-42	1942-43	Average
Minimum storage (start of year) .... inches	[2] 4.0	6.2	5.0	[3] 6.1
Wilting point less minimum storage [4] .... do	1.9	−.3	.9	[3] −.2
Field-capacity storage .... do	17.0	(5)	17.0	[3] 17.0
Field capacity less minimum storage .... do	13.0	(5)	12.0	----------
Rain to start percolation .... do	25.8	(5)	15.9	[8] 20.8
Mean evaporation rate:				
Wetting period .... inches per day	.025	.037	.019	.027
Percolation period .... do	(6)	(5)	.030	[5] .030
Entire soil below wilting-point storage .... days	(7)	88	(7)	(7)

RAINFALL DISPOSITION (INCHES)

Item	1940-41	1941-42	1942-43	Average
Rainfall	47.8	16.8	45.1	[8] 40.4
Interception loss	0	0	0	0
Surface runoff [9]	----------	----------	----------	----------
Rainfall reaching soil	47.8	16.8	45.1	[8] 40.4
Evaporation	16.2	8.7	16.7	[8] 16.4
Percolation and runoff	29.4	[10] 9.3	26.3	[8] 27.8

[1] Calculations based on 5-foot soil depth.
[2] Measured at time of trenching.
[3] Excluding 1940–41; includes minimum storage measurement of 7.1 inches at start of 1943–44 hydrologic year.
[4] Wilting-point storage = 5.9 inches.
[5] Insufficient rain to raise soil to field capacity.
[6] Losses may have occurred but were too small to be detected by sampling method used.
[7] In 1940–41 first foot reached wilting point; in 1942–43 second foot reached wilting point. Mean not significant.
[8] Two-year average; 1941–42 not included because rain was not sufficient to wet through soil.
[9] Not measured.
[10] Soil not wet through; hence this is runoff only.

the amounts of erosion or runoff can be made for these 2 years. In 1941–42, however, the residuum of 9.3 inches represents surface runoff because at no time during that year was the soil wet deep enough to start percolation. It can be concluded, therefore, that runoff represents a relatively large part of the percolation-plus-runoff quantity in the other 2 years as well. Evaporation from the bare plot was 16.2 inches in 1940–41 and 16.7 inches in 1942–43, 3.5 inches and 1.6 inches less than evapo-transpiration from the chamise plot in these 2 years. When the saving in interception loss is included the total reduction in evaporative losses caused by denudation in these years stands at 7.4 inches and 4.9 inches respectively. This suggests, as did the Bass Lake results, that for deep soils substantial increases in total water yeld can be obtained by complete denudation, but that a considerable part of the yield under these conditions comes in the form of flash storm flows of surface runoff, which may be heavily laden with sediment.

RAINFALL DISPOSITION ON THE MONROE CHAPARRAL WATERSHED

The foregoing plot studies have shown the disposition of precipitation that falls upon land surfaces in several parts of California. They have shown that differences in climate, environment, soil, and vegetation are reflected in differences in interception loss, surface runoff, evapo-transpiration, and percolation. Also they

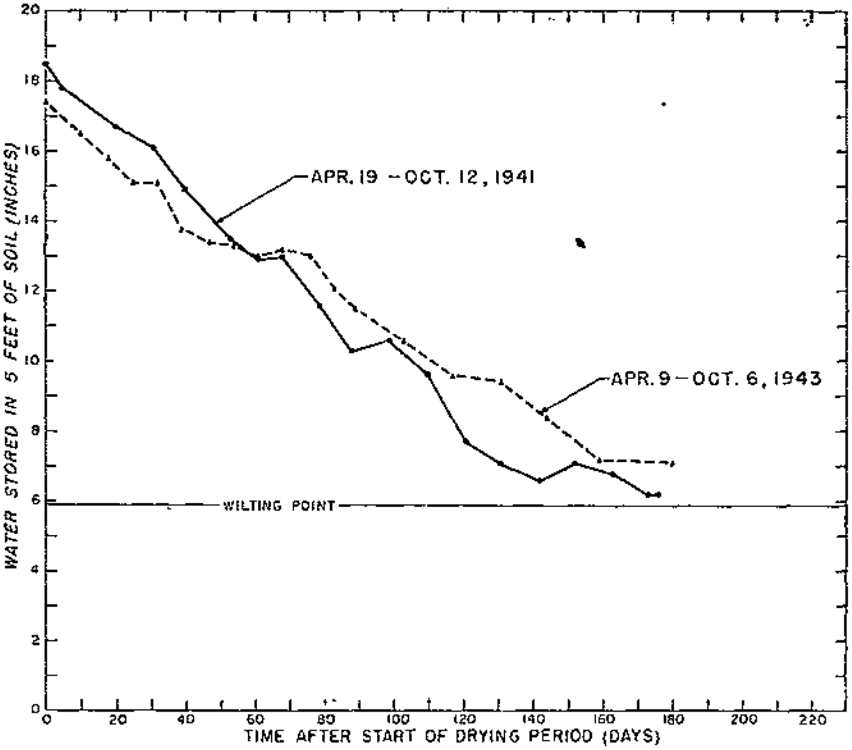

FIGURE 24.—Water storage in the soil of the San Dimas bare plot during the summer drying periods of 1941 and 1943.

have indicated that changes can be excepted in the course of water disposition as the result of partial or complete removal of the vegetation cover.

There is a further opportunity in studies of this kind: that of interpreting plot results in terms of water yield from entire watersheds. The North Fork, Bass Lake, and San Dimas plots have not provided the information needed to do this because they sampled only single spots on hillside slopes of the watersheds in which they were located. From their records could be obtained neither the assurance that they represented average watershed conditions, nor any certainty that they sampled the range in conditions found on the watershed.

The Monroe Canyon study was planned specifically to determine the water yield of a watershed. Analysis of the soil-moisture data and their interpretation in terms of the disposition of precipitation upon this watershed fall into three stages:

1. Determination of characteristics of the soil-water cycle and the disposition of rainfall which are representative of all 14 moisture-sampling plots, supplemented by study of how the cycles and dispositions vary in relation to the soil and environmental conditions of the individual plots.

2. Conversion from plot-determined values of rainfall disposition to values applicable to the watershed as a whole.

3. Interpretation of watershed-wide rainfall disposition in terms of losses and yield of water from the watershed.

RESULTS FROM PLOTS ON THE WATERSHED

There was little difference in total annual rainfall between the 2 years of study; 31.4 inches fell in 1943-44 and 30.7 inches in 1944-45, both close to the 10-year watershed average of 32.0 inches. However, there were differences in storm size and occurrence. Also, each of the 14 plots differed somewhat in soil and environmental characteristics (table 3). As a result soil-water storage at any particular time varied from plot to plot (table 14). It was apparent, though, that seasonal variations in soil water were closely similar for all plots. Therefore it was possible to define for each year an annual cycle of soil water that applied qualitatively to all the plots (fig. 25).

In terms of rainfall disposition, the plots showed differences that could be attributed principally to differences in soil characteristics. Between October 18 and December 5, 1943, the 1.6 inches of rain received by all plots was lost by interception (table 15) and evapo-transpiration (table 14). The next two storms (that of December 5 and that of December 9 to 12) brought a total of 4.1 inches of rain, of which 0.3 inch was estimated to have been lost by interception. The remaining 3.8 inches, which entered the soil, was sufficient to bring 7 of the 14 plots to field-capacity storage and to start percolation from two of them (plots 7 and 17). The plots wet through in these storms were those with available water storage less than 4.4 inches and included most plots with soils 3 and 4 feet deep. Five of the remaining plots reached field-capacity storage during the 3.6-inch storm of December 17 to 22. During this storm 10 plots yielded percolation. With 1.3 inches of rain between December 28 to 31, the remaining two plots (11 and 21) reached field capacity. Judging from this wetting sequence, it can be said that differences in wetting time were attributable primarily to differences in quantities of water required to bring the several plots to field-capacity storage.

In this regard it is important to remember that only a very general relation exists between the quantity of available water storage and soil depth. This is so because the proportion of solid rock contained in this soil is unrelated to soil depth (see page 19). The volume occupied by this rock was deducted from the volume of soil in each plot in order to arrive at the volume of soil material that could hold appreciable quantities of water. It is this volume of soil material rather than gross soil volume that determines available water storage.

The quantities of water lost by evapo-transpiration during the percolation period of 1943–44 (table 14) were measured during the three major interstorm intervals: January 6 to 23, January 27 to February 3, and February 8 to 19. As was mentioned earlier,

TABLE 14.—*Soil-water storage and rainfall disposition in the Monroe Canyon soil-moisture plots, 1943–44 and 1944–45*

1943–44 [1]

Plot aspect and number	Soil depth	Field capacity less wilting-point storage	Minimum storage, start of year	Evapo-transpiration, wetting period	Rain to start percolation	Date of field capacity replenishment	Evapo-transpiration, percolation period	Mean evapo-transpiration rate, percolation period	Total percolation and runoff [2]	Date end of percolation period	Evapo-transpiration, drying period	Date wilting-point storage reached	Minimum storage, end of year	Wilting point less minimum storage	Total evapo-transpiration
	Feet	*Inches*	*Inches*	*Inches*	*Inches*		*Inches*	*In./day*	*Inches*		*Inches*		*Inches*	*Inches*	*Inches*
Plots on northerly hillsides:															
9	3	5.9	3.2	1.4	6.7	Dec. 22	4.9	0.082	13.9	Mar. 13	8.5	Aug. 2	3.2	0.4	14.8
17	3	3.1	1.6	1.4	5.0	Dec. 12	1.7	.028	19.6	...do...	6.2	June 25	1.4	.4	9.3
18	3	3.7	2.0	1.4	5.7	...do...	1.8	.030	18.4	...do...	7.4	July 14	1.7	.7	10.6
10	4	7.2	4.3	1.4	9.3	Dec. 22	5.1	.085	13.7	...do...	8.4	Oct. 18	4.4	0	14.9
11	5	8.6	3.0	1.4	10.6	Dec. 31	2.9	.048	13.9	...do...	10.5	Sept. 20	3.0	.2	14.8
15	5	4.8	2.8	1.4	6.8	Dec. 22	1.8	.030	18.0	...do...	8.0	June 28	2.3	.6	11.2
Average	4	5.6	2.8	1.4	7.4	....	3.0	.050	16.2	....	8.2	....	2.7	.4	12.6
Plots on southerly hillsides:															
2	3	3.5	3.0	1.4	5.7	Dec. 12	3.2	.053	18.3	Mar. 13	7.5	July 6	1.3	1.1	12.1
7	3	3.1	1.8	1.4	4.4	...do...	1.8	.030	19.5	...do...	6.5	June 25	1.3	.4	9.7
20	3	4.3	2.3	1.4	5.7	...do...	3.6	.060	16.9	...do...	7.1	May 27	2.0	.6	12.1
16	4	3.5	1.7	1.4	5.7	...do...	2.1	.035	19.3	...do...	5.9	June 25	1.7	.5	9.4
22	4	4.0	1.8	1.4	5.7	...do...	3.0	.050	17.4	...do...	7.0	June 20	1.7	.3	11.4
4	5	4.4	3.3	1.4	6.8	Dec. 22	3.5	.058	16.9	...do...	6.8	Aug. 23	3.4	.2	11.7
8	5	6.6	5.0	1.4	9.3	...do...	2.4	.040	16.2	...do...	9.1	May 31	4.6	.4	12.9
21	5	5.6	4.4	1.4	10.6	Dec. 31	1.6	.027	16.2	...do...	9.9	July 8	4.0	1.2	12.9
Average	4	4.4	2.9	1.4	6.7	....	2.6	.044	17.6	....	7.5	....	2.5	.6	11.5
Grand average	4	4.9	2.[illegible]	1.4	7.0	....	2.8	.047	17.0	....	7.8	....	2.6	.5	12.0

Footnotes at end of table.

TABLE 14.—*Soil-water storage and rainfall disposition in the Monroe Canyon soil-moisture plots, 1943-44 and 1944-45—Continued*

1944–45 [3]

Plot aspect and number	Soil depth	Field capacity less wilting-point storage	Minimum storage, start of year	Evapo-transpiration, wetting period	Rain to start percolation	Date of field capacity replenishment	Evapo-transpiration, percolation period	Mean evapo-transpiration rate, percolation period	Total percolation and runoff [2]	Date end of percolation period	Evapo-transpiration, drying period	Date wilting-point storage reached	Minimum storage, end of year	Wilting point less minimum storage	Total evapo-transpiration
	Feet	*Inches*	*Inches*	*Inches*	*Inches*		*Inches*	*In./day*	*Inches*		*Inches*		*Inches*	*Inches*	*Inches*
Plots on northerly hillsides:															
9	3	7.6	3.2	0	8.7	Nov. 14	5.5	0.050	13.6	Mar. 26	9.0	Aug. 12	3.6	0.2	14.5
17	3	3.6	1.4	0	4.0	do	4.5	.041	18.4	do	5.5	May 25	1.5	.4	10.0
18	3	2.4	1.7	0	2.6	do	(4)	(4)	(4)	do	4.7	July 11	2.4	.6	(4)
10	4	9.7	4.4	0	10.1	do	5.4	.050	11.9	do	11.9	Sept. 4	3.7	.2	17.3
11	5	9.3	3.0	0	9.9	do	5.7	.052	10.8	do	11.2	Sept. 20	3.8	0	16.9
15	5	4.8	2.3	0	6.2	do	4.1	.038	17.2	do	6.4	Sept. 10	3.1	.5	10.5
Average	4	6.2	2.7	0	6.9		5.0	.046	14.4		8.1		3.0	.3	13.8
Plots on southerly hillsides:															
2	3	2.1	1.3	0	4.6	Nov. 14	3.8	.035	19.1	Mar. 26	4.7	June 13	2.2	1.5	8.5
7	3	2.9	1.3	0	6.0	do	5.3	.049	18.2	do	4.9	June 22	1.4	.5	10.2
20	3	4.3	2.0	0	4.6	do	3.3	.030	18.2	do	7.1	July 7	1.9	.7	10.4
16	4	3.8	1.7	0	4.7	do	4.6	.042	17.4	do	6.5	June 6	1.7	.5	11.1
22	4	5.0	1.7	0	6.3	do	3.8	.035	17.9	do	6.9	July 7	1.6	.3	10.7
4	5	6.9	3.4	0	7.4	do	3.3	.030	14.5	do	10.7	Aug. 20	3.4	.2	14.0
8	5	5.0	4.6	0	5.9	do	3.0	.028	18.1	do	8.2	July 11	3.8	1.0	11.2
21	5	4.6	4.0	0	6.6	do	5.5	.050	15.5	do	7.3	June 22	4.2	1.3	12.8
Average	4	4.3	2.5	0	5.8		4.1	.037	17.4		7.0		2.5	.8	11.1
Grand average	4	5.1	2.6	0	6.3		4.4	.041	16.2		7.5		2.7	.6	12.2

[1] Average precipitation = 31.4 inches; average interception loss = 2.7 inches.
[2] Surface runoff not measured, but considered to be insignificant.
[3] Average precipitation = 30.7 inches; average interception loss = 2.2 inches.
[4] Sampling errors do not permit calculation.

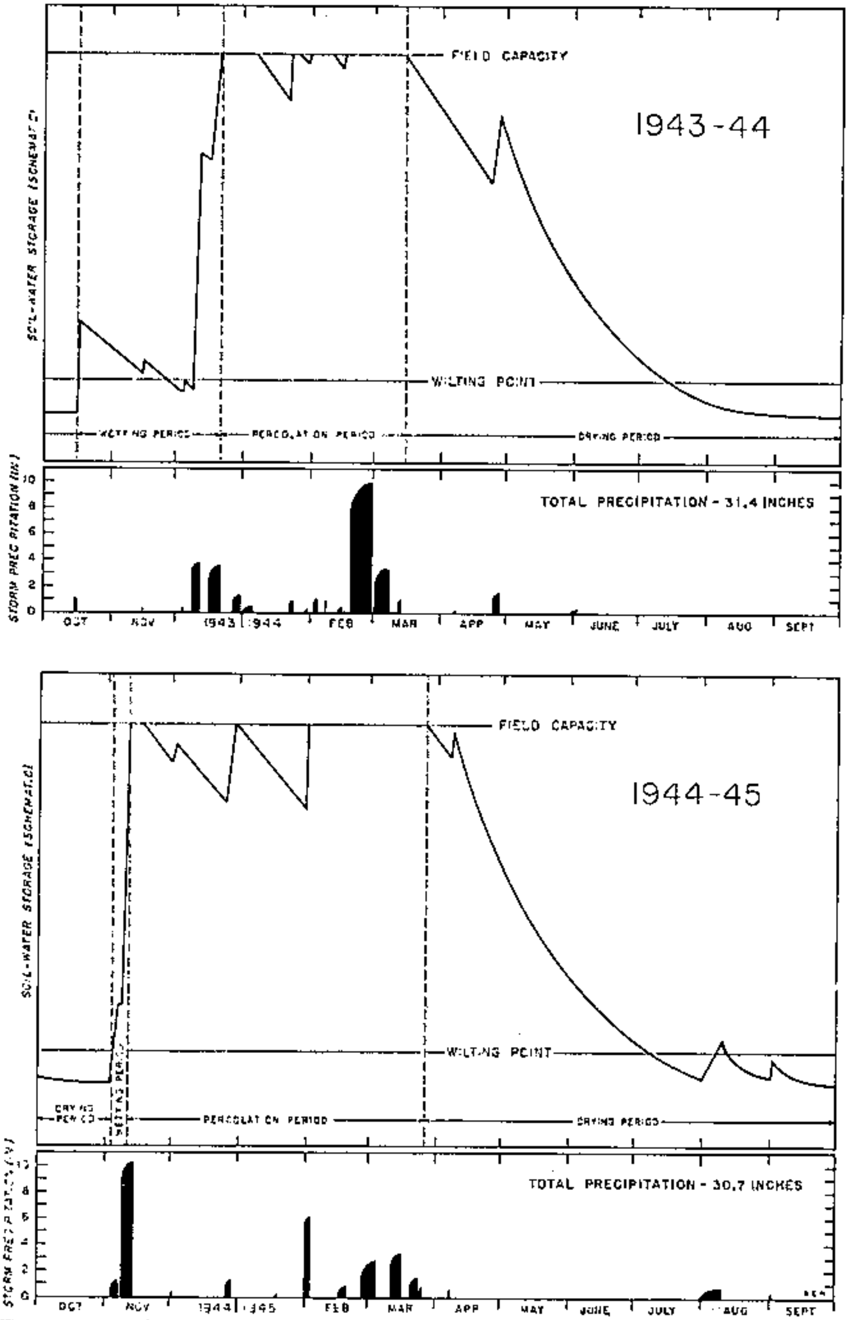

FIGURE 25.—Seasonal variations in water stored in the soil of the Monroe Canyon soil-moisture plots, 1943-44 and 1944-45. (Taken from table 14; the slopes in the water-storage graphs have no quantitative significance; they serve only to separate each cycle into periods of increasing, decreasing, or constant storage.)

TABLE 15.—*Inches depth of rainfall, interception loss, and water entering soil in Monroe Canyon, by storms, 1943-44 and 1944-45*

1943–44

Storm date	Mean rainfall [1]	Interception loss [2]	Water entering soil
1943:			
Oct. 18	1.3	0.1	1.2
Nov. 16	.3	.1	.2
Dec. 5	.3	.1	.2
Dec. 9–12	3.8	.2	3.6
Dec. 17–22	3.6	.2	3.4
Dec. 28–31	1.3	.1	1.2
1944:			
Jan. 2–6	.5	.1	.4
Jan. 23–24	.9	.1	.8
Jan. 26–27	.1	.1	0
Jan. 30–31	.3	.1	.2
Feb. 3–4	1.1	.1	1.0
Feb. 8	.9	.1	.8
Feb. 14–15	.4	.1	.3
Feb. 17	.2	.1	.1
Feb. 19–20	9.9	.5	9.4
Mar. 2–8	3.4	.2	3.2
Mar. 13	1.0	.1	.9
Apr. 8	.2	.1	.1
Apr. 26–28	1.6	.1	1.5
May 31–June 3	.3	.1	.2
Total annual	31.4	2.7	28.7

1944–45

Storm date	Mean rainfall [1]	Interception loss [2]	Water entering soil
1944:			
Nov. 4–7	1.3	.1	1.2
Nov. 9–14	10.3	.5	9.8
Dec. 2	.4	.1	.3
Dec. 27–29	1.3	.1	1.2
1945:			
Jan. 19	.2	.1	.1
Jan. 31–Feb. 3	6.2	.3	5.9
Feb. 17–20	.8	.1	.7
Feb. 27–Mar. 5	2.8	.2	2.6
Mar. 12–17	3.3	.2	3.1
Mar. 21–24	1.5	.1	1.4
Mar. 25–29	.8	.1	.7
Apr. 8	.6	.1	.5
Aug. 1–10	.8	.1	.7
Sept. 2	.4	.1	.3
Total annual	30.7	2.2	28.5

[1] Mean of 12 gages which sample the entire watershed.
[2] Interception-rainfall relation assumed to be the same as that found at the San Dimas mixed chaparral plot.

determinations could not be made during the remainder of the percolation period because of the very short intervals between storms. For this season evapo-transpiration quantities may be slightly low. The quantities range from 1.6 inches to 5.1 inches. In their range they show no positive relation to aspect, soil depth, or available water. The mean of 2.8 inches may therefore be taken as representative of the 14 plots as a group.

Mean evapo-transpiration rates (table 14). calculated for the total number of rain-free days during the percolation period, ranged from 0.027 inch per day to 0.085 inch per day. Like total evapo-transpiration during this period, they bear no significant relation to aspect or soil. The average value for all plots 0.047 inch per day, may therefore be taken as the rate best representing the plots as a whole.

The bulk of the percolation yielded by the plots came from the storms of December 17 to 22, December 28 to 31, January 2 to 6, and the three which occurred between February 19 and March 13. A few plots yielded percolation from the 1.1-inch storm of February 3 to 4, and the 0.9-inch one on February 8. But these plots yielded little percolation because a considerable part of each storm's contribution was utilized in replacing evapo-transpiration losses suffered previously. Total percolation for this year averaged 17.0 inches; surface runoff was considered negligible. Percolation from individual plots ranged from 13.7 inches to 19.6 inches.

Summer evapo-transpiration accounted for the greatest portion of the year's evaporative losses of soil water. During the drying period, from March 13 to November 4, all available water in all plots was lost to the atmosphere; and in addition the soil dried 0.5 inch below wilting point to reach minimum storage. Besides these losses 2.1 inches of summer rain were returned to the atmosphere by interception and evapo-transpiration.

As the summer drying period advanced and wilting-point storage was approached, evapo-transpiration rates decreased: a progression that was also noted in the other plots of the present study. There was little evidence, however, that summer drying rates were closely related to the total quantity of water lost during this period. All but two plots reached wilting-point storage between late May and mid-August. These two plots held the largest quantities of available water, and they did not reach wilting-point storage until after mid-September. This suggested a relation between drying time and available water storage, but such a relation is by no means clearly defined when the other plots are considered.

The same interplot relations were shown in 1944–45. Although total rainfall was much the same this year as the previous, its distribution through the rainy season was different. All plots were wetted to field capacity and yielded percolation in the second storm of the year, which, together with the one shortly before it, brought 11.6 inches of rain to the watershed. Evapo-transpiration during the ensuing interval of 2½ months ranged from 3.0 to 5.7 inches. This dry interval was terminated by a storm (January 31 to February 3) which brought 6.2 inches of rain, enough to replace all previous evapo-transpiration losses and to yield percolation from all plots. From February 3 to March 26 storms were so frequent that no significant evapo-transpiration losses were detected on any of the plots, and all rain reaching the ground was considered to contribute to percolation.

Mean evapo-transpiration rates during this year's percolation period ranged from 0.028 inch per day to 0.052 inch per day and, as in the year before, bore no relation to soil or aspect characteristics. The average rate, 0.041 inch per day, is only slightly less than that calculated for 1943–44. Total percolation, with a mean of 16.2 inches, ranged from 10.8 to 19.1 inches and again showed evidence of being associated with quantity of available water.

Drying period water losses this year accounted for all available water in all plots and an additional 0.6 inch, on the average from below the wilting point. Besides this, 1.8 inches of summer rain was lost by combined interception and evapo-transpiration. This year the drying period was entered 2 weeks later than the year before. There was no noticeable change in evapo-transpiration rates as a result of this shift, so that about the same time was required this year as the previous to bring the plots to wilting-point storage. One plot (number 17) reached wilting-point storage in late May, but most plots did not reach this level until sometime between mid-June and early September. Again there was some suggestion that wilting-point storage was reached later by plots with greater available water storage.

WATER LOSSES AND YIELD CALCULATED FOR THE WATERSHED

Determination of rainfall disposition in Monroe Canyon requires the conversion of annual evapo-transpiration and percolation from a plot to a watershed-wide basis. If this conversion can be effected with some assurance of reliability, it is possible to calculate rainfall losses and water yield of the watershed.

Analysis of the 14 moisture-sampling plots showed that evapotranspiration is not clearly related to aspect or soil depth, but that it does bear some relation to the amount of available water storage in the soil. Hence each year's data were plotted, and a regression line was fitted by the method of least squares (fig. 26). These relations for the 2 years are presented in the following equations and apply to the range of available water storage between 2 and 10 inches:

$$1943\text{–}44 \qquad E = 7.1 + A$$

$$1944\text{–}45 \qquad E = 6.2 + 1.1A$$

In these equations A represents available soil-water storage (inches depth of water in the soil between wilting-point and field-capacity storage), and E represents annual evapo-transpiration loss, also measured in inches depth. From the nature of the processes involved, it seems probable that the equations would remain linear in type year after year, but that the numerical constants would vary, depending upon the amount of annual rainfall and its distribution throughout the year.

The two equations provide part of the information needed to convert plot data so that they apply to the entire watershed. The remaining information is provided by data obtained in the soil survey of Monroe Canyon (p. 19). As a part of this survey 110 pits were dug throughout the watershed, and the available water storage of the soil from each pit was calculated from laboratory measurements of wilting-point and field-capacity moisture. Measurements of soil depth, apparent soil density, and rock content provided means for expressing these moisture contents in inches depth. One hundred and ten pits, distributed as widely as these, may be considered to represent a fair sampling of this 875-acre watershed (p. 21). It is possible, then to group the pits into available water classes, assign to the mean of each class the evapo-

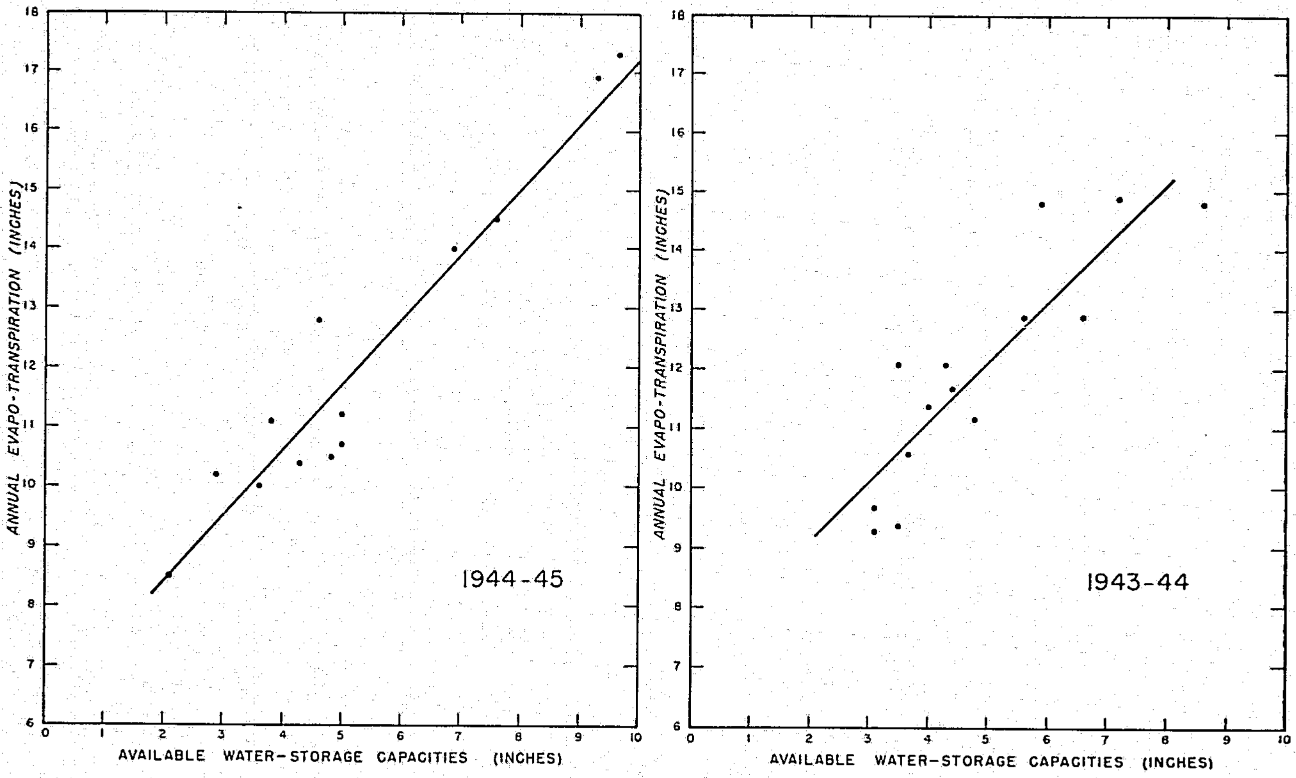

FIGURE 26.—Relation between annual evapo-transpiration and available soil-water storage in the Monroe Canyon moisture-sampling plots, 1943-44 and 1944-45. (Differences in available water storage between the 2 years are due to shifting of the sampling within each plot.)

transpiration quantities calculated from the equations, and calculate mean watershed evapo-transpiration weighted in accordance with the number of pits in each class.

The distribution of pits by available water-storage classes was:

Class (inches):	*Mean storage (inches)*	*Pits (number)*
0-1.9	0.8	50
2-3.9	2.8	19
4-5.9	4.9	16
6-7.9	6.6	12
8-9.9	8.8	8
10-11.9	10.4	2
12-13.9	13.6	2
14-15.9	14.1	1

The 14 moisture-sampling plots do not cover the range shown by the pits. They cover only the range of classes from 2 to 9.9 inches, which include 55 of the 110 pits; and it is within this range that the two equations define the relations of evapo-transpiration to available water. Extrapolation is therefore required in order to determine evapo-transpiration in both lower and higher classes.

The linear relation shown by the two regression equations is assumed to hold in the extrapolation. Although specific data to support this assumption are lacking, certain considerations lend justification to it. In the first place, extrapolation on the low water-storage side is small while on the high side only 5 pits go beyond the range of the sampled plots. Errors due to extrapolation are therefore minimized.

In the second place, overestimation of evapo-transpiration in the class of smallest available water storage may not be as great as it appears to be at first glance. The equation for 1943–44 shows that 8.1 inches of water are lost from soil having an available water storage of 1 inch. This simply means that the available water in the shallow soils which make up this class is lost and replenished a number of times each year. Such intermittent replenishment has been noted within the top foot of all plots in this study, and is due to the rapid drying of the surface soil layer between periods of rain. It is likely that evapo-transpiration losses from soils with no available water storage (represented by 9 pit locations occupied by rock outcrop) is overestimated. The 1943–44 equation shows a loss of 7.1 inches of water from these bare rock surfaces. But water can be stored in surface depressions and cracks in the rock, which means, as explained above, that these locations, too, can lose considerable water.

In the third place, the evapo-transpiration calculated from the equation probably underestimates the losses from some of the deeper soils. At 12 locations the soil contained so much rock that pits could not be dug deeper than 6 feet, yet it was evident that soil and roots were present beyond this depth. At these locations available water storage was calculated for 6 feet of soil. Because the true water storage was greater than calculated, it is likely that evapo-transpiration losses, too, were greater.

There is no assurance that possible underestimations of evapo-transpiration from the deeper soils counteract possible overestimations from the most shallow ones. But the foregoing considerations suggest that linear extrapolation of the evapo-transpiration equation offers the best method available in this study for minimizing bias in the calculation of watershed evapo-transpiration.

When calculations were made, using the equations and the required extrapolations, mean evapo-transpiration losses for the watershed were found to total 10.6 inches in 1943–44 and 10.0 inches in 1944–45. The corresponding average quantities determined for the 14-moisture-sampling plots were 12.0 and 12.2 inches.

Up to this point no separate consideration has been given to evapo-transpiration losses from the riparian zone which occupies 7 of the 875 acres of Monroe Canyon. These losses have been assumed tacitly to be the same as those elsewhere in the watershed. This is quite possibly true during that part of each year when water is equally available for evapo-transpiration in the upland areas and within and adjacent to stream channels. But during the late summer and fall the upland soils lose all their available water and evapo-transpiration rates become extremely small. At this same time, however, water may still be flowing in or on the sands of the stream channels, and riparian losses may be appreciable.

No measurements of riparian water losses were made in Monroe Canyon, but an estimate can be made from the water losses of this kind determined in nearby Coldwater Canyon *(2, pp. 88-121)*. Coldwater Canyon is similar to Monroe Canyon in vegetation, topography, and climate, and lies about 30 miles to the east in the same mountain range. These similarities suggest the validity of transferring data from one watershed to the other. Furthermore, preliminary hydrograph analysis in Monroe Canyon indicates that the losses from equal areas of riparian vegetation here and in Coldwater Canyon are very nearly the same.

The riparian zone of Coldwater Canyon lost 54 inches of water in the 6-month period from May 1 to October 31. This quantity represents the loss for only part of the summer drying period, and therefore does not account for the entire summer riparian loss in Monroe Canyon. In 1943-44 the drying period in Monroe Canyon lasted from March 13 to November 4, in 1944-45 from March 26 to November 1. Assuming that the mean rate of 9 inches a month applies to March as well as later, the total summer riparian loss in Monroe Canyon becomes 69.6 inches in 1943–44 and 64.5 inches the next year. Part of the riparian loss has already been accounted for, by considering it equal to losses elsewhere in the watershed during the drying period. In 1943–44 the riparian loss accounted for in this way amounted to 6.1 inches; in 1944–45 it amounted to 5.8 inches. The remaining riparian loss amounted to 63.5 inches in 1943–44 and 58.7 inches in 1944-45.

These losses correspond to 0.51 inch and 0.47 inch, respectively, when calculated in inches depth over the entire watershed, as shown in the following sample calculation:

63.5 acre-inches per acre = 444 acre-inches over the 7 acres of the riparian zone;

444 acre-inches = 0.51 inch depth over the 875 acres of the entire watershed.

Hence it can be concluded that 0.5 inch must be added to the average evapo-transpiration loss of the watershed each year, as representing dry-season riparian losses in excess of those previously calculated for the watershed as a whole.

In summary, an accounting of rainfall disposition can be presented which considers the following factors: (1) Rainfall calculated as a watershed mean from the records of 12 rain gages; (2) interception loss calculated from measurements made in the mixed chaparral plot; (3) evapo-transpiration calculated from records of soil-water storage; (4) additional riparian evapo-transpiration losses, taken as equivalent to those in Coldwater Canyon; and (5) percolation through the soil, which is the quantity of rainfall not accounted for by losses (2), (3), and (4).[5] The final disposition is shown in the following tabulation:

	1943-44 (inches)	*1944-45 (inches)*
Rainfall	31.4	30.7
Interception loss	2.7	2.2
Evapo-transpiration loss	11.1	10.5
Percolation through soil	17.6	18.0

The quantities of percolation shown in the tabulation represent what may be called the water yield of the watershed, that is, percolation through the soil plus any surface runoff that may have occurred. The tabulation provides no clue as to how this water is yielded from the watershed. All it shows is that in these years evaporative water losses accounted for a good deal less than half the rainfall. The remainder, it was concluded, left the watershed as stream flow and as underground flow through fractures and other water passageways in the underlying rock.

RELATION OF STREAM FLOW TO WATER YIELD

Stream-flow rates (figs. 27 and 28), recorded continuously at the mouth of Monroe Canyon, provided data with which to compare channel flow with underground flow. This comparison is of particular interest because it offers an opportunity to appraise stream flow as a measure of watershed yield. Hydrologists have frequently suggested that in many watersheds some water each year is yielded to downstream areas as flow which does not appear in streams within the watershed. In the Monroe Canyon study only that portion of the water yield appearing as stream

[5] No attempt has been made to correct evapo-transpiration or percolation for the quantity of rainfall intercepted by the stream channel and adjacent impervious area, and diverted directly into channel flow. This contribution to water yield represents 100 percent runoff from a varying area averaging less than 1 percent of the total watershed area. The quantities involved are estimated at less than 0.25 inch for each of the 2 years of the study.

flow at the gaging station could be measured. Estimates of underground flow quantities could be made, however. Calculations made in the study provided a measure of all water available for flow from the watershed. Hence the difference between stream flow and total water available for flow was considered to have left the watershed as underground flow.

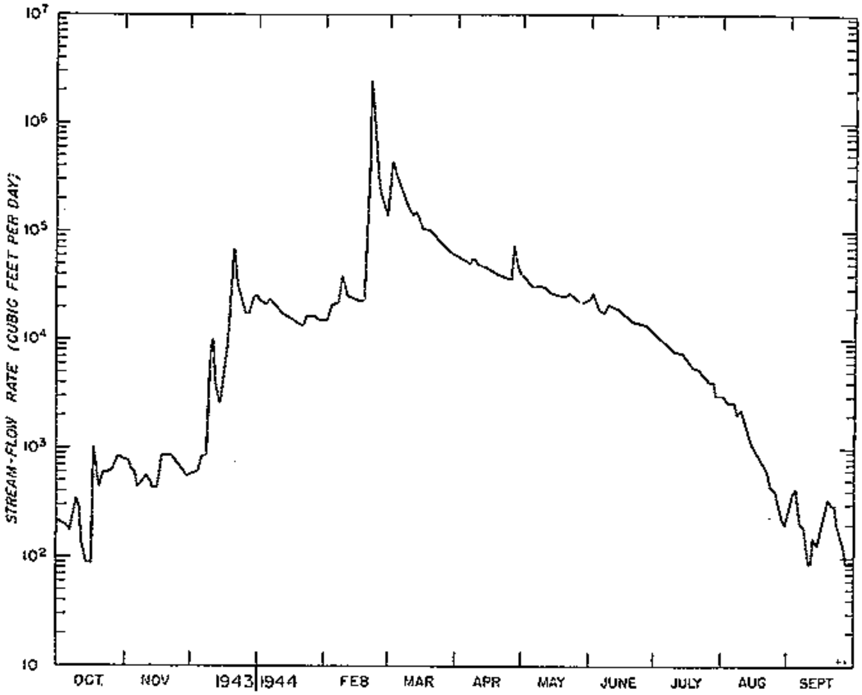

FIGURE 27.—Hydrograph of daily stream flow in Monroe Canyon, 1943-44.

In order to establish the validity of underground-flow estimates it is necessary to study briefly some stream-flow characteristics and relate them to indications of water yield shown by the sampling plots. Answers to the following questions will reveal the stream-flow characteristics of this watershed and the nature of its water yield:

1. How is the initial recharge of stream flow related to the first occurrence of percolation through the watershed soil?

2. How are surges in stream flow related to times of percolation?

3. How much of the precipitation reaching the watershed each year does not appear as stream flow until the year following?

4. If there is no carryover of water from year to year, how much of the calculated percolation leaves the watershed as stream flow each year? How much percolation is not accounted for and what is the fate of this excess water?

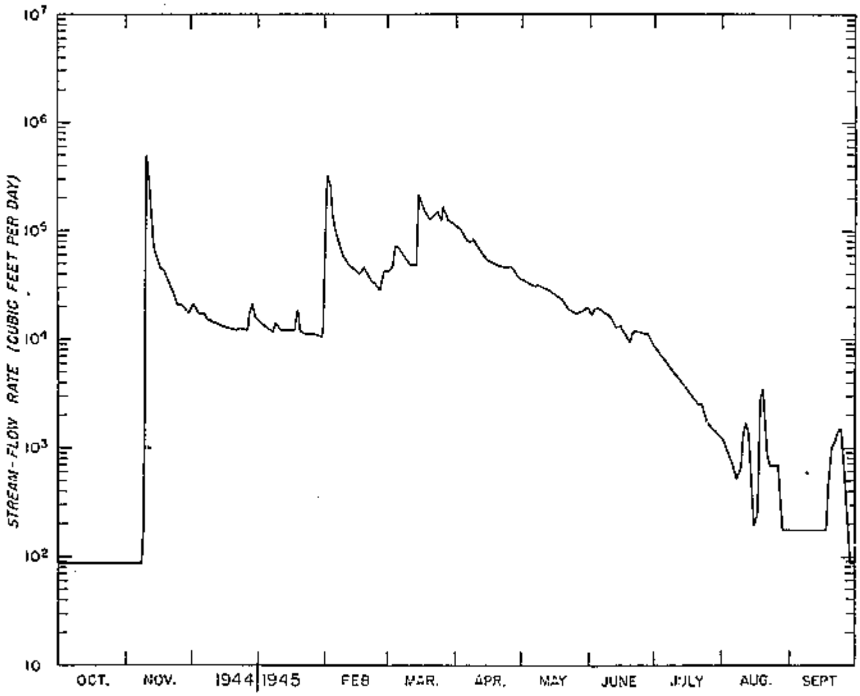

FIGURE 28.—Hydrograph of daily stream flow in Monroe Canyon, 1944-45.

In answer to question 1, it will be noted that in each year a significant increase in stream flow did not take place until the date of the storm that was shown in the soil-water storage analysis to have produced percolation through the soil (figs. 29 and 30). Thus in 1943–44 the first occurrence of percolation in the sampling plots as well as the initial rise in stream flow came during the storm of December 9 to 12. In this storm a small quantity of percolation was yielded by two of the plots. In 1944–45 the corresponding storm was that of November 9 to 14, which yielded more than 5 inches of percolation from 10.3 inches of rain. Rains previous to these served only to raise the soil water toward field-capacity storage. In this watershed, therefore, it appears that the initial rise in stream flow corresponds closely in time with the general replenishment of field-capacity storage in the soil of the sampling plots.

The answer to question 2 is found in further study of the Monroe Canyon hydrograph. Surges in stream flow occurred on the dates of most storms during both years (figs. 27 and 28). However, these surges were not all of the same relative magnitude. In fact they can be separated into two distinct types. One type, which might be called minor surges, raised stream flow above the general level of the hydrograph for only a few days. These surges always coincided with the occurrence of rains that were insuffi-

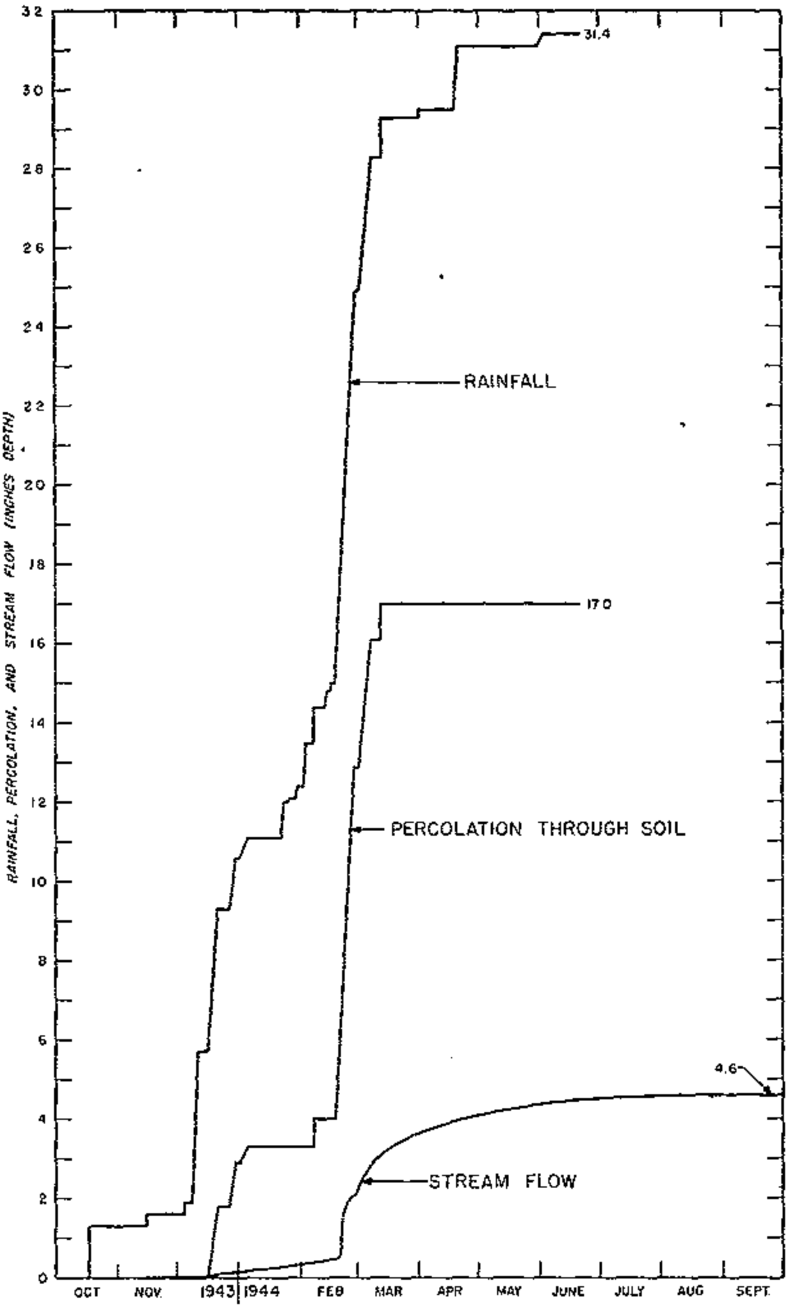

FIGURE 29.—Cumulative rain, percolation, and stream flow in Monroe Canyon, 1943-44.

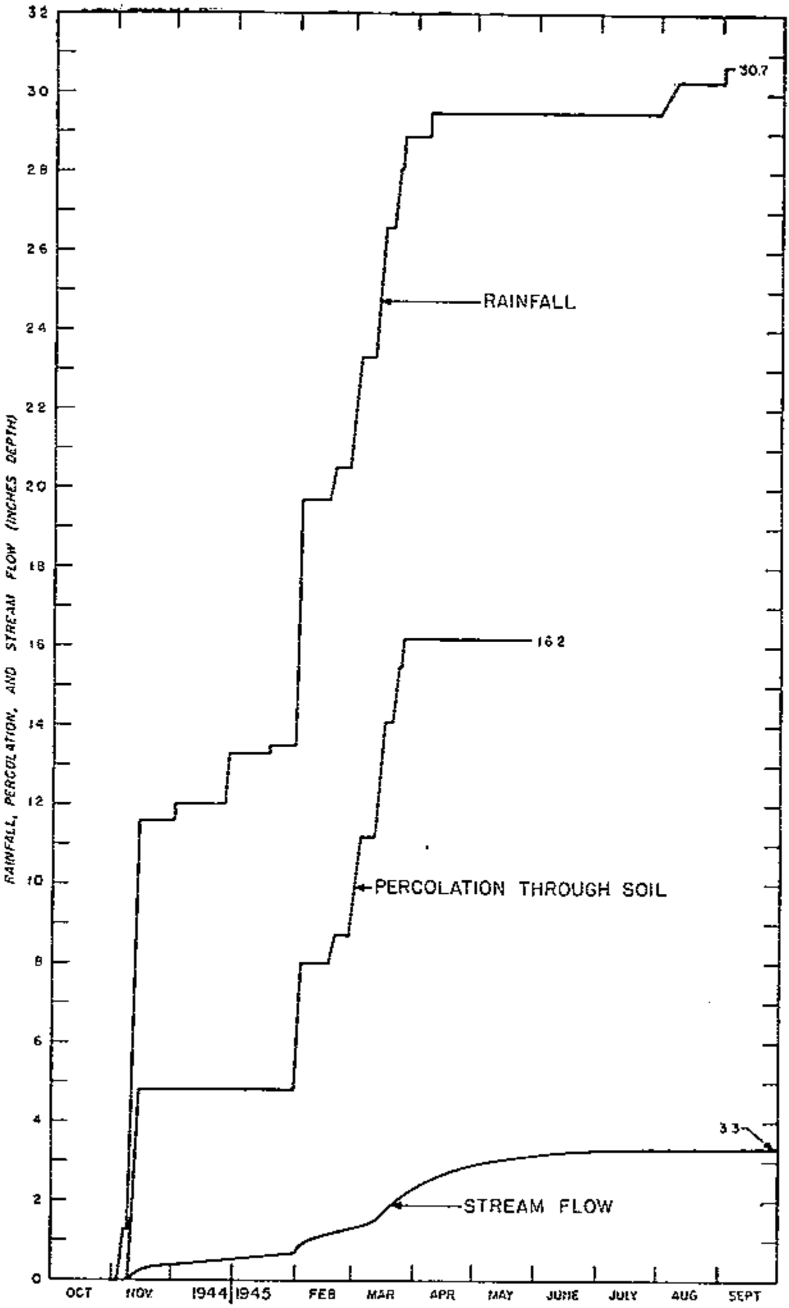

FIGURE 30.—Cumulative rain, percolation, and stream flow in Monroe Canyon, 1944-45.

cient to replenish field-capacity storage. From both hydrograph and soil-water storage evidence the minor surges appear to represent largely the flow of rain water intercepted by the stream channel rather than the flow stimulated by increases in ground-water storage.

The other type, major surges in stream flow, brought about sustained rises in the hydrograph. These surges invariably coincided with storms that yielded percolation through the soil. They were therefore associated with significant increases in ground-water flow. Although the peak flows of the major surges included rain caught as channel interception, the long-sustained increased flow which followed must have been made up of water supplied to the stream by water percolating through the soil.

These two types of stream-flow surge can be clearly distinguished in figures 29 and 30. The minor surges (primarily channel interception) make no perceptible impression upon the cumulative hydrograph. The major surges, occurring during periods of percolation through the soil, are shown as abrupt increases in the slope of the stream-flow curve.

Question 3 concerns the carryover of stream flow from one year to the next. In October 1943 the stream-flow rate was negligible, and it did not increase perceptibly until December 9, when percolation was initiated (figs. 27 and 28). In 1944 negligible rates were reached by the end of August, and again no appreciable rise was noted until percolation started during the storm of November 9 to 14. In 1945 negligible rates were reached once more in early August.

These periods of negligible stream flow are shown better if stream flow is cumulated through each year (figs. 29 and 30). No perceptible quantity of water was yielded by the channel between October 1 and December 17, 1943, August 1 and November 9, 1944, and after August 1, 1945. It appears, therefore, that during these 2 years substantially all rain water available for stream flow was yielded from the watershed each year as channel flow before the advent of the next rainy season. Certainly this would not be the case every year; perennial stream flow has been observed in this watershed during several years of high rainfall. But it can be assumed that in 1943-44 and 1944-45 all stream flow each year was the result of that year's rainfall.

Knowing that each year's stream flow was the result of that year's rain and, further, that there was no appreciable carryover of stream flow from one year to the next, it is possible to answer question 4 by comparing the percolation calculated each year for the soil of the entire watershed with the stream flow resulting from it. The amount of annual rainfall accounted for as percolation and stream flow was:

	1943-44 (inches)	*1944-45 (inches)*
Percolation through the soil	17.6	18.0
Stream flow	4.6	3.3
Percolation less stream flow	13.0	14.7

These percolation quantities are corrected for riparian water losses; because they are calculated for the watershed as a whole, the quantities vary somewhat from the 14-plot average shown in figures 29 and 30.

It is immediately apparent that during these 2 years stream flow accounts for only about one-quarter of the water which percolated through the soil mantle into the rock mass beneath. Because evaporative water losses have been accounted for, percolation not leaving the watershed as stream flow cannot be considered lost as evaporation or transpiration. Instead it must be considered to have left the watershed as flow through the underlying rock mass. Just where, at what elevations, and when this water left the watershed cannot be ascertained at present. All that can be established now is the time of delivery of this water into the underlying rocks as percolation, a calculation of the amount so delivered, and the assurance that this water left the watershed as underground flow rather than stream flow.

In view of the extensively faulted rock underlying the Monroe Canyon watershed, it is not surprising that all percolating water does not reappear as stream flow within the watershed. However, the magnitude of the underground yield of water becomes apparent only when all other losses—interception, evapo-transpiration, and stream flow—have been accounted for, as has been possible in this study. When this is done it becomes evident that stream flow provides an inadequate measure of water yield under geologic conditions such as prevail in this watershed.

DISCUSSION AND CONCLUSIONS

Quantitative application of research findings such as these must be limited to the region within which the study was made. The results are so strongly influenced by local conditions of climate, soils, and vegetation that they cannot safely be extended very far from the study areas. The processes involved in rainfall disposition, however, are the same in all semiarid regions, and therefore the procedures used in this study have wide usefulness. The following discussion shows ways in which the findings of the present study can aid in the solution of important watershed problems in many places.

Determining Quantity of Water Yielded by a Watershed

Total annual rainfall provides an extremely rough index of watershed yield of semiarid regions. This is so because no simple relation exists between annual rainfall and the evaporative water losses which constitute the difference between rainfall and yield. There are several kinds of evaporative water losses, and each kind is related to rainfall in a different way. When each loss is evaluated separately it is possible to calculate water yield with considerably greater accuracy than is possible when annual rainfall alone is used as the index.

The first evaporative loss which must be calculated is that of precipitation intercepted by vegetation. It has been shown that in forest and brush areas studied in the mountains of California interception loss is directly related to storm rainfall. It is possible, therefore, to calculate the amount of water thus withheld from a watershed if the relation between interception loss and rainfall is known, and if adequate storm-by-storm records of rainfall are available. For the larger storms interception loss is a linear function of storm rainfall but not a constant percentage of the quantity of rain. Within relatively narrow limits, however, the annual interception loss does represent a constant percentage of annual precipitation. Under natural vegetation conditions at North Fork, Bass Lake, and San Dimas, the annual interception losses were about 5 percent, 12 percent, and 8 percent, respectively, of the annual rainfall (table 16). It is probable that the nearly constant annual percentage loss by interception is due to the occurrence, year after year, of much the same pattern of storms.

TABLE 16.—*Mean water losses of the study plots.*

Location and treatment	Soil depth	Evapo-transpiration		Evapo-transpiration rate		Interception loss in relation to annual rainfall	Years included in means
		Annual	Drying period [1]	Wetting period [2]	Percolation period [2]		
	Feet	*Inches*	*Inches*	*In./day*	*In./day*	*Percent*	
North Fork, woodland chaparral:							
Natural	3	14.1	7.9	0.020	0.074	5	4
Burned	3	12.2	7.3	.009	.070	(3)	2
Bare	3	12.6	6.4	.021	.070	0	4
Bass Lake ponderosa pine:							
Natural	6	16.9	12.9	.042	.008	12	5
Burned	6	20.2	17.6	.035	(4)	12	5
Bare	6	11.4	10.0	.019	.007	0	3
San Dimas, chaparral:							
Mixed chaparral	5	18.0	10.8	.053	.029	8	2
Ceanothus	5	18.4	11.7	.056	.040	[5] 8	2
Chamise	5	19.0	13.3	.061	.030	[5] 8	2
Bare	5	16.4	12.2	.022	.030	0	2
Monroe Canyon	3	11.1	6.6	.028	.044	[5] 8	2
	4	12.5	7.4	.027	.047	[5] 8	2
	5	12.9	8.8	.024	.040	[5] 8	2

[1] Drying period usually extends from March to October.
[2] Calculated on basis of number of days between storms.
[3] Not measured.
[4] Losses too small to be detected by sampling method used.
[5] Assumed same as for mixed chaparral.

The rain remaining after subtracting interception loss is that which reaches the soil. Of this a part, not determined in the present study, can be retained by and evaporated from the litter covering the soil surface. Kittredge (*15*) has estimated that field-capacity storage of the average mass of forest litter is between 0.1 and 0.2 inch of water. During the rainy season, therefore, it is unlikely that forest litter, being moist at that time, can retain as much as 0.1 inch of rain from each storm. Rain retained by litter may constitute a measurable source of water loss in dense forest stands, but it can be considered negligible in chaparral or other plant associations which produce only thin litter layers with extremely low field-capacity storage. In the North Fork natural plot, which has as deep a litter cover as any of the brush plots studied, the field capacity of the litter cover is 0.02 inch (*20, p. 13*). Thus, even if it were possible for the litter to dry completely after each storm, the yearly interception loss would be less than 0.5 inch.

The next loss to be determined is evapo-transpiration from the soil during the rainy season. In order to simplify this discussion it is assumed that surface runoff is negligible in amount,[6] and that all water reaching the soil goes into storage within it. In the region to which this discussion has immediate application the first rain of the rainy season enters soil which contains no water available to plants. During the early part of the rainy season evapo-transpiration between storms removes water from the soil at a fairly constant rate. If this rate is known it is possible to calculate soil-water storage at any time during the wetting period, and to determine the evapo-transpiration losses up to the time when the soil has been raised to field-capacity storage.

Evapo-transpiration rates during this period range, in the present study, from 0.02 to 0.06 inch per day under natural plant cover, and vary with soil depth and field-capacity storage (table 16). Somewhat different evapo-transpiration rates prevail during the percolation period, when the entire soil mass remains more or less at field-capacity storage. During the percolation period the natural plots showed loss rates between 0.01 and 0.07 inch per day. Generally in each plot the relation between the periods was such that a low loss rate during the wetting period was followed by a high loss rate during the percolation period, and conversely. As a first approximation the assumption of the same rate during both periods will lead to no great error. It is suggested that 0.04 inch per day for the Bass Lake area and 0.06 inch per day for the other areas represent useful approximations of evapo-transpiration rates between storms during the rainy season.

During the wetting and percolation periods, then, water can be considered lost from the soil between storms at a relatively constant rate. But this rate applies only as long as water from any storm remains in the soil. During the early part of the rainy season the water contribution of an entire storm may be lost before the next one occurs. At San Dimas as much as 4 inches of rain per year was lost in this way from early-season storms. The application of the evapo-transpiration rates in table 16 permits calculation of the amount of rain which, because of these early season losses, makes no contribution to water yield, as well as losses of stored soil water during the main part of the rainy season.

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[6] If runoff is appreciable some means must be employed for its determination, storm by storm. A method of utilizing plot infiltration measurements has been outlined by Rowe (*19*), and several other investigators have described methods of direct evaluation that make use of hydrograph analysis (*9, 10, 11*). Much more study will be needed, however, before entirely satisfactory techniques are available for this important determination.

The third type of water loss is a constant amount representing the summer drying of the soil mass. The present study has shown that during the summer and fall dry season all water between wilting-point and field-capacity storage is lost from the soil. The quantity of water lost in this way varies with soil texture, density, and depth. In the present study it ranged from 3.8 to 11.1 inches under natural vegetation. But the summer water loss does not stop here; additional water is lost primarily by evaporation from the upper soil layers. This evaporation reduced total soil-water storage to a fall minimum 0.2 inch to 1.4 inches below wilting-point storage. Besides this, all rain entering the soil during the drying period is lost by evapo-transpiration. Summer water loss therefore comprises approximately half an inch in addition to storage between wilting point and field capacity, plus any rain which falls and enters the soil during this period. Total water losses from the natural plots during the drying period ranged from 6.6 to 13.3 inches out of annual evapo-transpiration losses which ranged from 11.1 to 19.0 inches.

With these losses evaluated it becomes possible to calculate annual water yield. First, a constant percentage of the year's rainfall is deducted as interception loss. Second, the soil-water loss for intervals between storms is calculated, based upon the average evapo-transpiration rate and the amount of water stored in the soil at the end of each storm. From this the total amount of evapo-transpiration during the rainy season is determined. Third, during the dry season it can be assumed that all soil water available to plants will be lost, plus an additional half inch to bring the soil to minimum storage, plus all rain which enters the soil during this season. The difference between the sum of these losses and annual rainfall represents watershed yield, or in watersheds having appreciable areas of riparian vegetation, watershed yield plus riparian water losses. The determination of riparian water losses requires a special type of stream-flow analysis which, so far, has received insufficient research attention.

This method of water-yield determination will be found most useful for watersheds that yield part of their water as underground flow. Underground flow moves in subsurface channels, which in the southern California mountains are provided by deeply weathered or highly fractured fault zones, and deep alluvium (*23*). In watersheds so constituted effluent stream flow often falls far short of carrying the entire water yield of the watershed, so that stream flow alone cannot be relied upon to provide a measure of total yield.

Determining the Time of Percolation Through the Soil Mantle

It has been shown that in the areas covered by the present study rainfall contributes percolation water only during that portion of each year when the soil is held at or near field-capacity storage. Furthermore, percolation through the soil mantle is not continuous during this period. It takes place only during times of rain or snow melt and very shortly thereafter. Within no more than 2 or 3 days after a storm or after snow has disappeared from the ground surface, the soil mantle has drained to field-capacity storage and evapo-transpiration has started further depletion of stored soil water. The next storm must replenish field-capacity storage before percolation can once more begin.

The present study has demonstrated how the timing of percolation through the soil mantle can be determined by accounting for soil-water additions and losses. When the method is applied to an entire watershed it may be found that some parts of the watershed soil yield percolation earlier than other parts. Such differences in timing are most pronounced in watersheds containing bodies of different kinds of soil, vegetation, or land use. In order to detect differences of these kinds and to give them proper consideration, it is necessary to provide adequate sampling of all watershed conditions and situations.

By means of the analyses discussed in this paper, percolating water was followed only into the rock which lies beneath the watershed soil. Its subsequent flow through the rock and time of emergence from the watershed could not be traced because only a small part of the percolating water reappeared as stream flow. It is apparent that the underground path followed by remaining water, and the time of its outflow from the watershed, would depend upon topography, geologic structure, and watershed size and shape. However, consideration of the timing of watershed yield is beyond the scope of this paper.

Determining the Effects of Vegetation Treatment Upon Rainfall Disposition

Where water yield can be measured directly it will be desirable to make the final test of vegetation treatment by treating an entire watershed. Watersheds that can be successfully studied in this way are those whose entire yield can be measured as stream flow and water accumulated in underground basins downstream. Here plot studies can perform an important function. A wide variety of promising treatments can be studied on plots, without requiring the large outlays of money, material, and manpower needed for treating entire watersheds. Plot results will thus point out not only those treatments that merit further study on whole watersheds, but also the types of effects that may be expected.

In watersheads whose yield is made up of stream flow combined with a considerable amount of underground flow that cannot be measured (which may be the situation in much of southern California), it is not possible to measure directly the effect of treatment upon yield. Although treatment may change total yield, it will be possible to measure only changes in stream flow, and stream flow may not be related directly to total yield. Here plot studies perform an even more important function. Besides making it possible to test a variety of treatments on a small scale, they provide the only means of determining the total water yield of a watershed. Under these circumstances the study plots must be distributed throughout the watershed, and in such a way as to provide a reliable sample of the conditions found within it.

The two kinds of treatment used in the present study were annual burning and complete denudation. A summary discussion of the effects of these treatments upon rainfall disposition will exemplify the type of analysis possible for other kinds of treatment.

The elements of rainfall disposition influenced by treatment of vegetation in the present study were interception, surface runoff, evapo-transpiration, minimum storage during the dry season, and percolation. All these could be studied effectively on the plots. Quantitative determinations of soil-water storage, percolation, and evaporative losses were made, and they are applicable directly to much larger areas of the same soil and vegetation. Quantitative measures of surface runoff were obtained on small plots, but it may not be safe to apply surface-runoff volumes determined for plots to much larger areas because of the cumulative effects of length of slope upon runoff volume. For the present, at least, surface-runoff measurements must be considered more in a qualitative than a quantitative sense.

Annual burning removed all vegetation each year from the North Fork plot, but did not affect the tree cover of the Bass Lake plot. As a result there was a significant difference in the effect of burning upon interception loss in these two areas. At North Fork it was assumed that interception loss was made negligible, because during nearly the entire rainy season of each year the invading grasses and herbs were too small to withhold appreciable amounts of rain from the soil. At Bass Lake, on the other hand, interception by the trees was unimpaired by burning and, because undergrowth was extremely sparse, it was concluded that total interception loss also had been virtually unimpaired.

Neither evapo-transpiration nor minimum storage was significantly affected by burning (table 16). This is readily apparent in data obtained from the North Fork plots, but at Bass Lake the differences in field-capacity storage between natural and burned plots must be taken into account.

As burning had no significant effect upon evapo-transpiration, it must be concluded that such treatment would increase water yield, including here both surface runoff and percolation, only to the degree that it would decrease interception loss. Thus under the conditions of burning practiced at Bass Lake no change in water yield would be expected; at North Fork a net increase of as much as 5 percent of the year's rainfall might be anticipated. In terms of total water yield this may be true, but in terms of usable water it is not necessarily true. Annual burning at both North Fork and Bass Lake greatly increased surface runoff (as a result of decreased infiltration rates) and correspondingly reduced the amount of percolation delivered to ground-water flow. Surface runoff carries with it the threat of flood and erosion. It is difficult and costly to control, and in all ways is a much less desirable type of flow than a yield that has its inception as percolation through the soil. In terms of water quality and yield of usable water, therefore, annual burning cannot be recommended as a practice of watershed management in the areas covered in the present study. Whether it is to be recommended elsewhere would have to be determined by similar kinds of analyses made under conditions typical of each of the other areas.

A denuded soil surface was maintained on one each of the North Fork, Bass Lake, and San Dimas plots, and living roots were excluded from the plot. This plot treatment therefore provided a soil from which water was lost only by surface runoff, percolation, or evaporation. The three plots responded to denudation in different ways because of differences in soil and exposure.

At North Fork the bare soil was shallow, relatively coarse-textured, and completely exposed to the atmosphere. Here evaporation rates were not significantly different from those on the natural and burned plots, and evaporation loss, likewise, was much the same. At San Dimas, with a deeper soil of finer texture, but still with complete exposure, evaporation rates during the wetting period were decreased by denudation. Annual evaporation losses here were some 2.5 inches less than evapo-transpiration losses from very similar soil occupied by chamise nearby. The greatest differences in evaporation loss were found between the bare plot at Bass Lake and the burned plot, which it resembled most closely. The soil here was deeper and of finer texture than that at either North Fork or San Dimas. Furthermore it was situated in a small forest opening where it was shaded and protected from wind by surrounding trees. In combination these circumstances reduced evaporation losses of soil water significantly. Owing to differences in available water storage in the three Bass Lake plots, direct comparison of evaporative losses cannot be made, but comparison of minimum and wilting-point storage indicates the effect of denudation. The minimum storage of both burned and natural plots was somewhat below the wilting point, yet the bare plot soil held at minimum storage nearly 4 inches of water in excess of the wilting point. Thus it appears that denudation is more effective in reducing evaporation losses from deep than from shallow soils, and from soils protected from full insolation than from those exposed to sun and wind.

The differences in exaporative losses of soil water are reflected in water yield. The combined surface runoff and percolation of the bare plot at North Fork was nearly equal to that of the burned plot. At Bass Lake, on the other hand, the elimination of interception loss combined with the reduced evaporation of soil water caused the percolation yield from the bare plot to exceed significantly that of the companion burned plot. These results lead to the conclusion that increases in usable water yield can possibly be achieved in this area if soils are deep, by reducing interception and evapo-transpiration losses, but only if surface runoff and soil erosion can be controlled.

The foregoing analyses demonstrate the kinds of interpretations that can be made of vegetation treatments studied in connection with watershed-management research. They show the qualitative as well as quantitative conclusions that such studies can reach. They can go far toward solving many watershed-management problems.

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COMMON AND BOTANICAL NAMES OF SPECIES MENTIONED

Alder, white	*Alnus rhombifolia*
Bearmat (Bear-clover)	*Chamaebatia foliolosa*
Bromes	*Bromus* spp.
Buckeye, California	*Aesculus californica*
Ceanothus, deerbrush	*Ceanothus integerrimus*
Ceanothus, buckbrush	*C. cuneatus*
Ceanothus, hairy	*C. oligantbus*
Ceanothus, hoaryleaf	*C. crassifolius*
Chamise	*Adenostoma fasciculatum*
Fescues	*Festuca* spp.
Incense-cedar	*Libocedrus decurrens*
Manzanita, Mariposa	*Arctostaphylos mariposa*
Maple, bigleaf	*Acer macrophyllum*
Mountain-mahogany, birchleaf	*Cercocarpus betuloides*
Mules-ears, Mariposa	*Wyethia elata*
Oak, California black	*Quercus kelloggii*
Oak, California scrub	*Q. dumosa*
Oak, interior live	*Q. wislizeni*
Peavine, Nevada	*Lathyrus nevadensis*
Pine, Digger	*Pinus sabiniana*
Pine, ponderosa	*P. ponderosa*
Pine, sugar	*P. lambertiana*
Poison oak, Pacific	*Toxicodendron diversilobum (Rhus diversiloba)*
Sage, black	*Salvia mellifera*
Sage, white	*S. apiana*
Sanicle, Menzies	*Sanicula menziesii*
Sumac, lemonade (Lemonade-berry)	*Rhus integrifolia*
Sycamore, California	*Platanus racemosa*
Tarweed, showy	*Madia elegans*
Tarweeds	*Madia* spp.
Willows	*Salix* spp.

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