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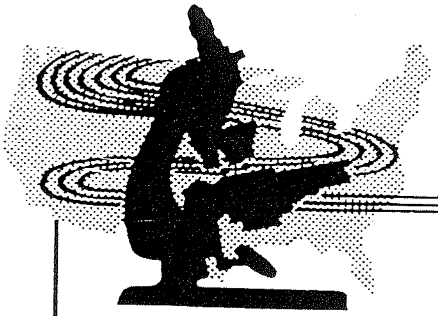

THE HYDROLOGY OF SEMIARID RANGELAND WATERSHEDS

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THE HYDROLOGY OF SEMIARID RANGELAND WATERSHEDS[1]

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In most of the Western United States, the major water-producing areas are in the higher mountains and are generally forested. About 500 million acres in the West contribute less than 1 inch of water a year to major streams. Hickok (6)[3] reported that approximately 10 percent of Arizona produces ½ inch or more of runoff per year, whereas 90 percent of the State yields less than ½ inch. Because of the extent of these low runoff-yielding watersheds, their total water production is important, and with improved management, they offer the possibility of increased yields of forage and water.

Research on rangeland hydrology was initiated by the former Research Division, Soil Conservation Service, U.S. Department of Agriculture, [at the request of its Operations Division,] and the work was transferred to the newly formed Agricultural Research Service in 1954. After a number of prospective research watersheds in Arizona, New Mexico, and Colorado were screened, an active program was initiated on the Walnut Gulch Experimental Watershed near Tombstone, Ariz., in 1953, and on the Alamogordo Creek Experimental Watershed near Santa Rosa, N. Mex., in 1954. In 1961 the Southwest Watershed Research Center, with headquarters in Tucson, Ariz., was established to continue the work. The research center staff has continued to measure rainfall and runoff on a number of small watersheds (1 square mile or less) near Safford, Ariz., and Albuquerque, N. Mex. (fig. 1). The Soil Conservation Service started these watersheds approximately 30 years ago. These data are valuable in considering a frequency analysis for such variable climates as those in the Southwestern United States. Recently, three small watersheds were instrumented at Fort Stanton, N. Mex., on a blue grama grassland area where cattle have not grazed in recent years and where the vegetation has returned to near climax condition.

WALNUT GULCH WATERSHED DESCRIPTIONS

Most of the research has been devoted to the 58-square-mile Walnut Gulch watershed near Tombstone, Ariz. Studies there are part of a comprehensive watershed research program to: (1) obtain information needed for planning and designing measures for controlling flash floods and sediment damage; (2) determine the optimum utilization of available water for local and downstream uses; and (3) determine the future water yield potential of semiarid rangeland watersheds as related to measures for their conservation and sustained forage production. These research objectives are being realized in two stages pursued simultaneously. The first stage involves identifying factors operative in the hydrologic system. The second stage involves evaluating the effect of range improvement practices and other experiments on the water and sediment balances.

Walnut Gulch is an ephemeral stream rising in the foothills of the Dragoon Mountains and joining the San Pedro River at Fairbank, Ariz. The study area, which extends to within 2 miles of Fairbank, comprises the upper 57.7 square miles of the drainage area and includes the town of Tombstone. Included within the watershed are rolling plains, narrow alluvial valleys, hills, and low mountains. Altitudes range from 4,000 feet above mean sea level at the outlet of the experimental area to slightly more than 6,200 feet in the Dragoon Mountains.

Tombstone has mild temperatures, limited rainfall, and high evaporation rates (low relative humidity) (fig. 2). The average frost-free season in Tombstone at an altitude of 4,580 feet is 237 days and has ranged from 205 to 277 days in the past 17 years. For January, the coldest month, the mean temperature is 47.1° F., and the mean minimum is 34.1° (23). For July the mean daily temperature is 79.0° with a mean maximum daily temperature of 92.7°. The mean maximum temperature for June is the highest, 94.1°, but the monthly mean is lower than for July, reflecting the lower nighttime temperatures. From July through September, moist unstable air masses generally advance into Arizona from the Gulf of Mexico and help produce a greater cloud cover. These air masses almost always produce moderate-to-intense thunderstorms, which develop most readily during the afternoon over the heated terrain. This

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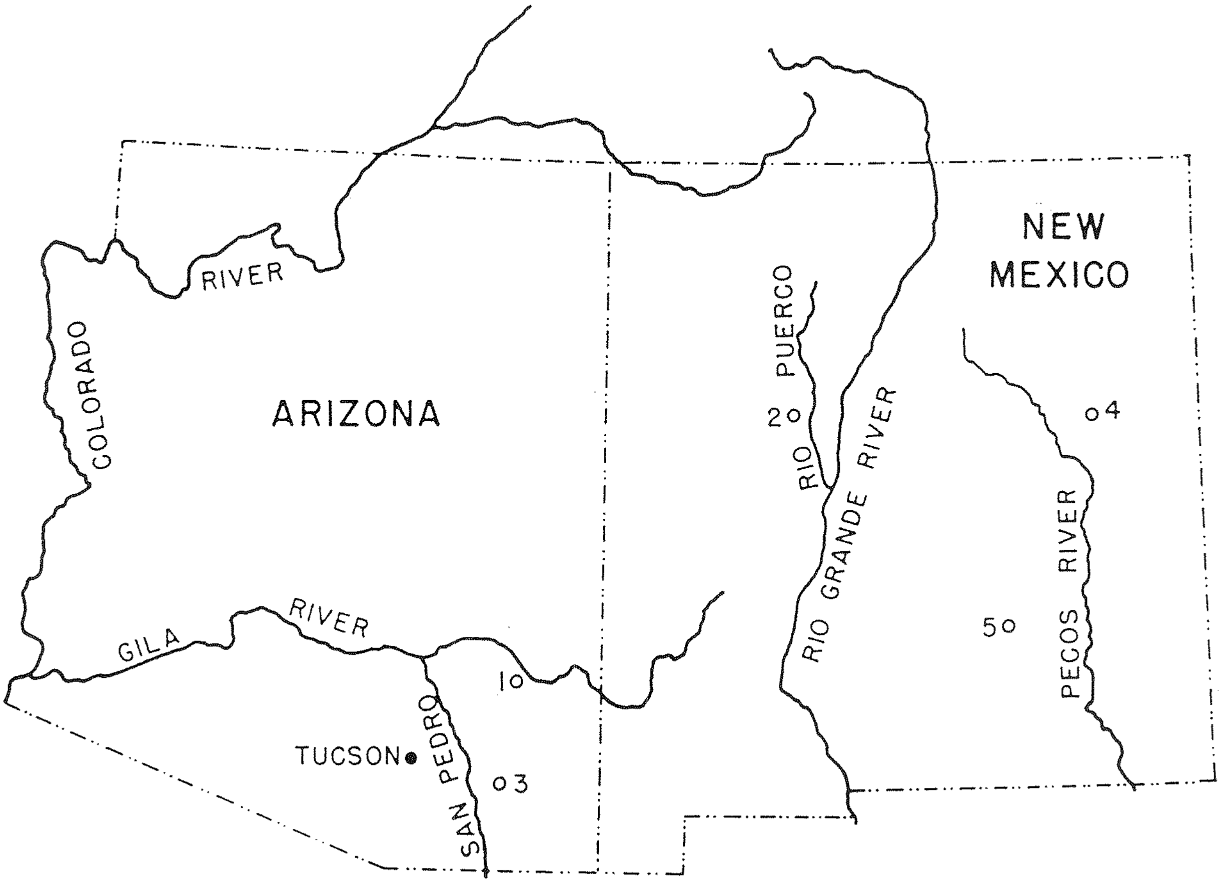
[3] Underscored numbers in parentheses refer to Literature Cited, p. 25.



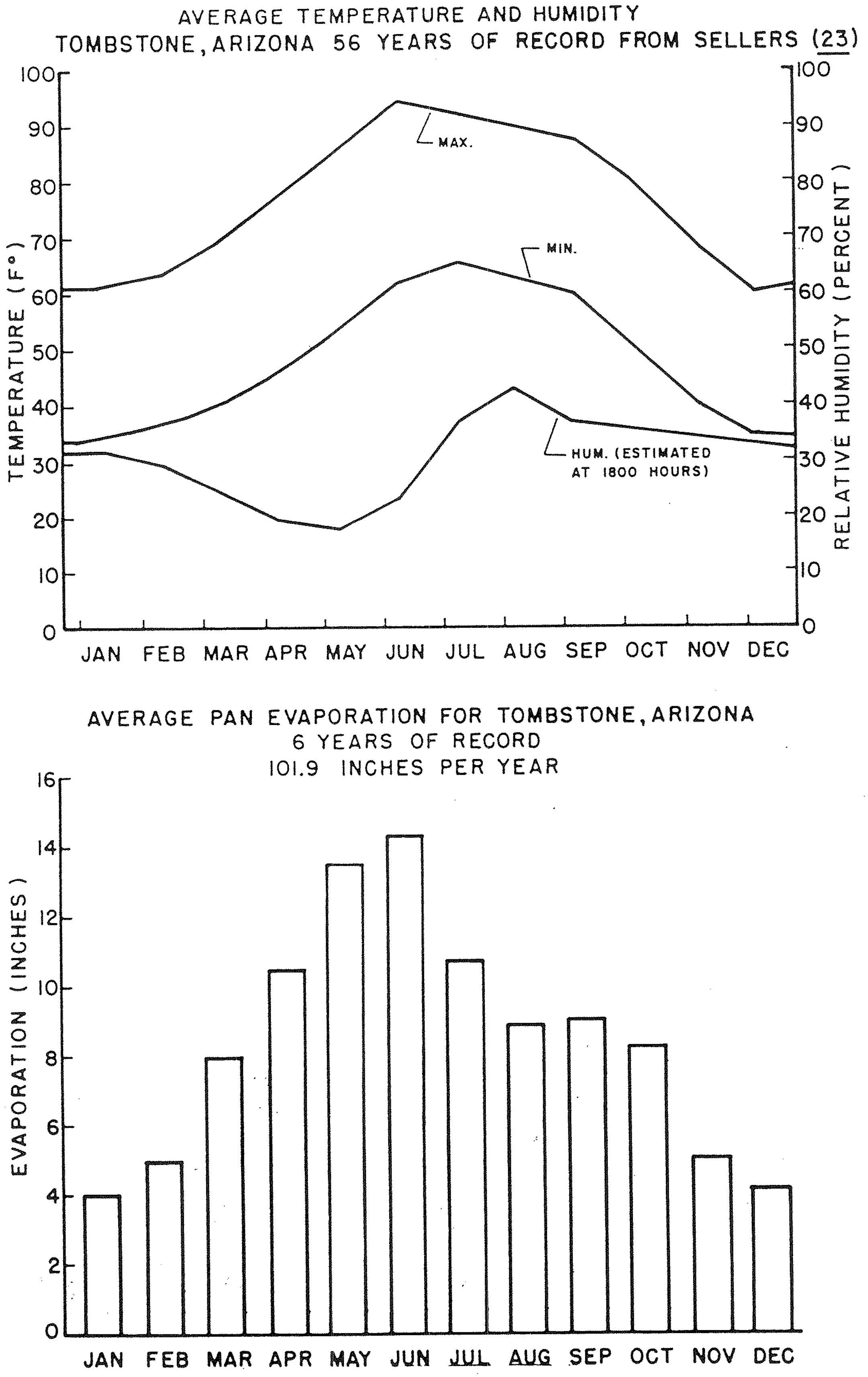
1. SAFFORD, ARIZ.
2. ALBUQUERQUE, N. MEX.
3. WALNUT GULCH NEAR TOMBSTONE, ARIZ.
4. ALAMOGORDO CREEK NEAR SANTA ROSA, N. MEX.
5. FORT STANTON, N. MEX.

Figure 1.—Location of experimental watersheds.

moisture and the associated cloud cover cause an abrupt decrease in the pan evaporation for July through September as shown in figure 2. The temperature extremes recorded for Tombstone are 6° and 110° F.

The climax vegetation of the Walnut Gulch area is

with varying amounts of the original grass species growing among them. The remainder of the area is grass-covered, with a few scattered shrubs of the same species as are found in the shrub-dominated areas. Whitethorn (*Acacia constricta* var. *vernicosa*) is the most


AVERAGE TEMPERATURE AND HUMIDITY
TOMBSTONE, ARIZONA 56 YEARS OF RECORD FROM SELLERS (23)

AVERAGE PAN EVAPORATION FOR TOMBSTONE, ARIZONA
6 YEARS OF RECORD
101.9 INCHES PER YEAR

Figure 2.–Climatic data for Walnut Gulch watershed. Average temperature and humidity from Sellers (23)

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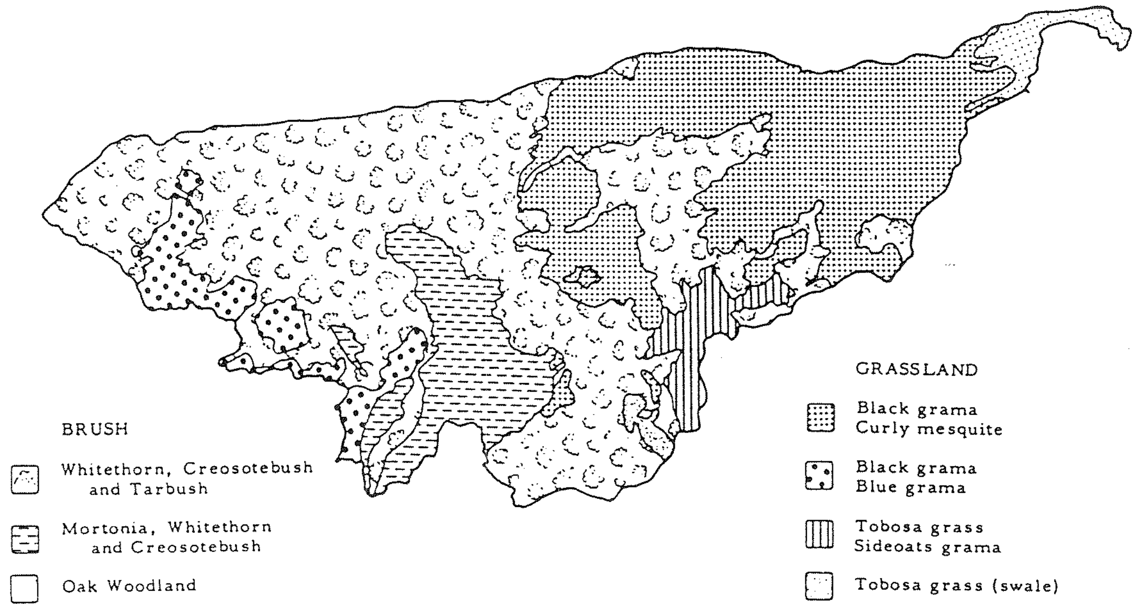
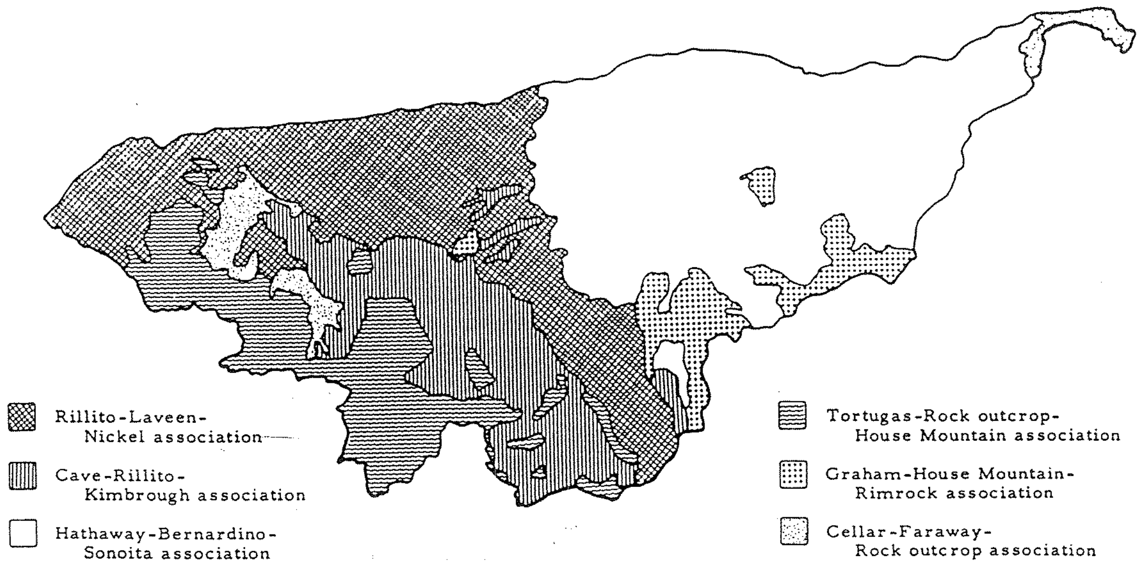


Vegetation Map



Soils Map

Figure 3.–Vegetation and soils maps, Walnut Gulch watershed.

southeastern igneous hills where clay soils occupy both swales and slopes.

The Rillito-Laveen-Nickel association (fig. 3) characteristically shows little profile development with depth and is arid and calcareous throughout, although some lime concentration is found within 40 inches of the soil surface. The Cave-Rillito-Kimbrough association is more shallow, has a cemented lime pan, and can occupy more level areas, although erosion has created slopes to 15 percent. The Hathaway-Bernardino-Sonoita association consists of soils from alluvial material overlying older soils. This association lies in the higher elevations of the watershed and includes soils that are noncalcareous and even slightly acid in the surface horizon. The Sonoita series is nongravelly to the calcareous subsurface or buried soil. The Tortugas-Rock Outcrop-House Mountain association is extremely shallow, cobbly, and has slopes up to 60 percent. Reflecting the limey parent material, these soils are usually very strongly calcareous. The Graham-House Mountain-Rimrock association also is very shallow. Conversely, the lime parent material changes in extrusive and volcanic rock that gives rise to clay soils in the Graham and Rimrock soil series. The soil pH in the surface is usually neutral or noncalcareous, although the degree of calcium saturation is high. This association also has cobbles or gravels in the profile. The last association, Cellar-Faraway-Rock Outcrops, is found on slopes to 60 percent, and is shallow, and stony to gravelly. The distinguishing characteristic of this group is its granitic-type rock parent material. All the soils of this group lie almost 18 inches over bedrock.

Walnut Gulch is geologically a high foothill alluvial fan. The Cenozoic alluvium is deep and consists of coarse-grained fragmental material, whose origin is traceable to present-day mountains on the flank of the watershed. The alluvium consists of clastic material ranging from clays and silts to well-cemented boulder conglomerates with little continuity of bedding. The topography consists of gently rolling hills incised by a youthful drainage system.

The mountainous portion of the watershed consists of rock types ranging in age from pre-Cambrian to Quaternary and has a rather complete geologic section. Rock types range from ridge-forming limestone to weathered granitic intrusions. The structural geology of the mountainous areas is complex, with much folding and faulting that affects the drainage pattern and the hydrology greatly.

Although the primary drainage pattern of Walnut Gulch is dendritic, local surface features create regions of widely differing patterns. Parallel drainage patterns are quite common in the upper elevations of the watershed, resulting in long, narrow subwatersheds. In most areas of the watershed, the geology controls the channel alinement. Resistant conglomerates are found on most stream bends, and some straight channel reaches coincide with major faults.

HYDROLOGIC FINDINGS

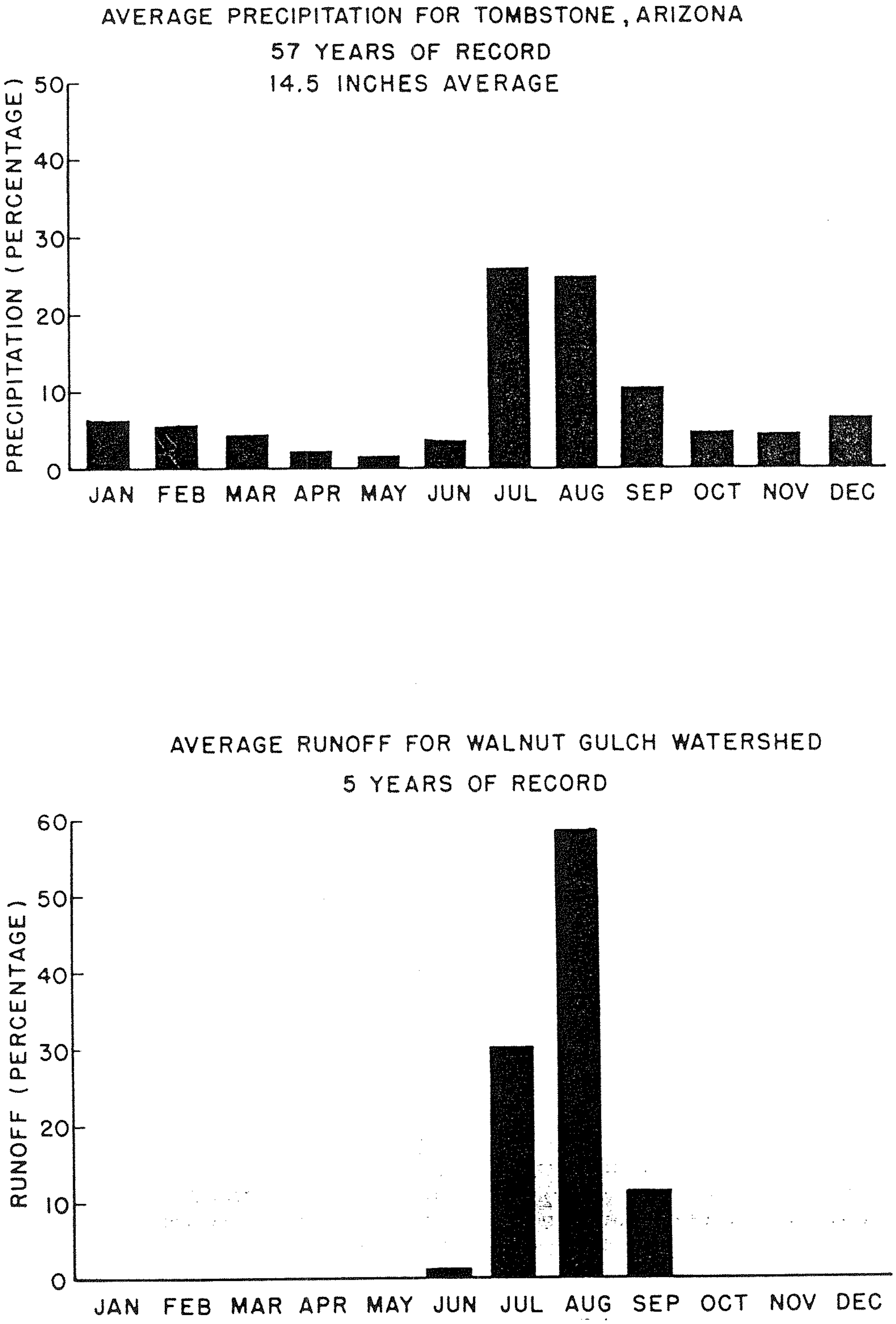
The complex nature of the hydrologic cycle makes it difficult to quantify each facet. It is generally impossible to develop theories and conclusions for universal application by observing the overall performance of complex watersheds, because a study watershed is seldom typical of any other watershed. Therefore, researchers study the basic individual hydrologic processes in a watershed that combine to make up the total watershed behavior. With such an understanding, it is possible to adjust the hydrologic processes as they are affected by varying conditions, and to predict, and perhaps improve, the behavior of rangeland watersheds in their initial state, as well as after treatment.

The important parameters that have been observed to strongly influence the behavior of semiarid watersheds can be classed under: (1) precipitation; (2) runoff generation; and (3) transit phenomenon.

Precipitation

Precipitation variability in time and space is one of the most difficult variables to measure in semiarid watersheds. Figure 4 shows the seasonal nature of the precipitation. The July, August, and September storms usually result from moist air masses advancing into Arizona from the Gulf of Mexico, and the winter storms result from cyclonic storms originating in the North Pacific Ocean. A small part of the winter precipitation is snow, which usually melts within a few days. Runoff from winter storms is limited to extremely small areas where the water storage potential of the soil and of the stream channel alluvium is minimal. Thus, the runoff shown in figure 4 results from the intense thunderstorms of July through September. Osborn (15) showed that although these storms vary greatly in amount, they are a dependable source of water on a seasonal basis. For 8 of the 11 years of record included in his analysis, a significant rainfall (0.25 inch or more) occurred on some part of the Walnut Gulch watershed on 30 to 50 percent of the days in July and August. Significant rainfall has been recorded on about 15 percent of the days in September and on less than 5 percent of the days from October to June.

Average precipitation on the Walnut Gulch watershed has varied widely during the study period. The low 7.1-inch average in 1960 is only one-half the 14.2-inch average high-year amount in 1955, and the 11.5-inch average from the rain gage network is considerably



AVERAGE PRECIPITATION FOR TOMBSTONE, ARIZONA
57 YEARS OF RECORD
14.5 INCHES AVERAGE

AVERAGE RUNOFF FOR WALNUT GULCH WATERSHED
5 YEARS OF RECORD

Figure 4.–Precipitation and runoff distributions on Walnut Gulch watershed.

below the 14.5-inch long-term average for the Tombstone gage (16). These averages may reflect some orographic influences because the long-term average precipitation at Fairbank, Ariz., (3,862 feet above sea level) is 11.67 inches, whereas Tombstone is near the center of the watershed. The orographic influence is greater during winter storms, when the moist air rises and crosses mountain ranges. Summer storms seem to occur randomly.

The annual point rainfall amounts also vary significantly across the watershed, and the annual minimum amounts often are only 50 percent of the maximum (fig. 5). The annual point rainfall amounts within the rain gage network have ranged from 4.7 inches in 1960 to 20.6 inches in 1958. By comparison, the annual precipitation for the Tombstone gage has ranged from 7.36 inches to 27.84 inches (57 years of record).

Convective thunderstorms on Walnut Gulch are characteristically limited in area, and are of high intensity and short duration. Runoff patterns are complicated further when more than a single cell occurs at one time. Figures 6 and 7 show examples of a single and a multicellular event. The simple storm of August 5, 1968, produced a single-peak hydrograph, whereas the storm of August 31, 1968, produced a complex hydrograph at the outlet of the watershed (fig. 8). The timing of the events also affects the runoff distribution. Had the timing of the storms in figure 7 been reversed, the storm on the lower portion of the watershed would have combined with the runoff from upstream to produce a high peak discharge (14). Osborn (14) states:

> For design purposes on watersheds of 100 square miles or less in the semiarid areas of the Southwest, precipitation depths for relatively short periods (15 to 60 minutes) for varying return periods and areas are needed, along with the probable size and separation of the storm cells in both space and time. For runoff designs involving larger watersheds, two probability estimates are needed—the probability of storms of certain intensities and sizes falling on tributary watersheds of finite size, and the probability of storms developing over a multi-tributary system in such patterns as to produce important volumes and peak discharges.

Figure 9 shows hyetographs of rainfall intensity at an individual gage and distribution graphs for the four precipitation events producing the largest discharges on Walnut Gulch. These storms lasted 2 hours or less and differed greatly in their intensity patterns. The patterns varied from the high intensities of the storms of August 17, 1957, and July 22, 1964, to the lower intensity of the 105-minute storm of August 25, 1968. Table 1 shows the maximum precipitation for selected durations of these storms. For comparison, data for one gage from three storms on the Alamogordo Creek Experimental Watershed, near Santa Rosa, N. Mex., are presented (20). Greater maximum point rainfall amounts have been observed on Alamogordo Creek than on Walnut Gulch. The storm of June 5, 1960, exceeded the maximum precipitation of record for storms lasting up to 30 minutes, as recorded by first-order Weather Bureau stations. (8). For this storm, 10 square miles of the watershed had 3.5 inches or more—a larger area and greater depth than ever recorded on Walnut Gulch. For comparison, the September 10, 1967, storm on Walnut Gulch covered less than 6 square miles to depths of 2 inches or more (19). The August 17, 1957, storm on Walnut Gulch probably covered a larger area than the September 10, 1967, storm, but the data for this storm were incomplete because in 1957, the precipitation network of 52 recording rain gages created "blind" areas for determining the storm area.

The maximum point rainfall amounts for the durations and storms shown in table 1 are plotted in figure 10. For comparison, the 5- and 100-year frequency point rainfall estimates from the U.S. Weather Bureau (5) are also shown. The Weather Bureau values are nearly identical for both watersheds. Most of these duration curves are considerably above the Weather Bureau's 5-year frequency graph. (Five-year frequency was selected because the four storms on Walnut Gulch and the three storms on Alamogordo Creek in 14-year records are nearly synonymous with the 5-year frequency.) The comparison of a point frequency with the observed maximum events from a network is not valid. Conditional frequencies that are difficult to determine are involved, and much work remains to relate point frequency to the network frequency. The probability of recording a maximum rainfall at one of the gages in a dense network is greater than that of recording a maximum at a single, fixed point. There is evidence, however, that the gage-year concept is valid when applied to records from gages in a dense network where the storms occur randomly. From 216 gage-years of record, based on record lengths of 3 to 7 years, Fletcher (3) obtained values nearly identical to the 57-year record of the gage at Tombstone, Ariz., near the network center. Thus, estimates of depth-frequency rainfall relationships based on records from dense rain gage networks may be more realistic than estimates based on longer point records. The length of the point record would seldom be suitable for estimating the 100-year frequency. Although Fletcher's conclusions appear valid for the network density and mean storm size included in his analysis, the relationship between these two parameters must be defined before the data can be extrapolated.

Runoff Generation

Initial runoff from the point where rainfall intersects the land surface (rain-site runoff) has been measured at more than 2 inches per year on Walnut Gulch. The effect of stream channels on water yield in even the smallest natural watershed is most important, however, and water yield on both a storm and an annual basis is highly correlated negatively with drainage area. To overcome

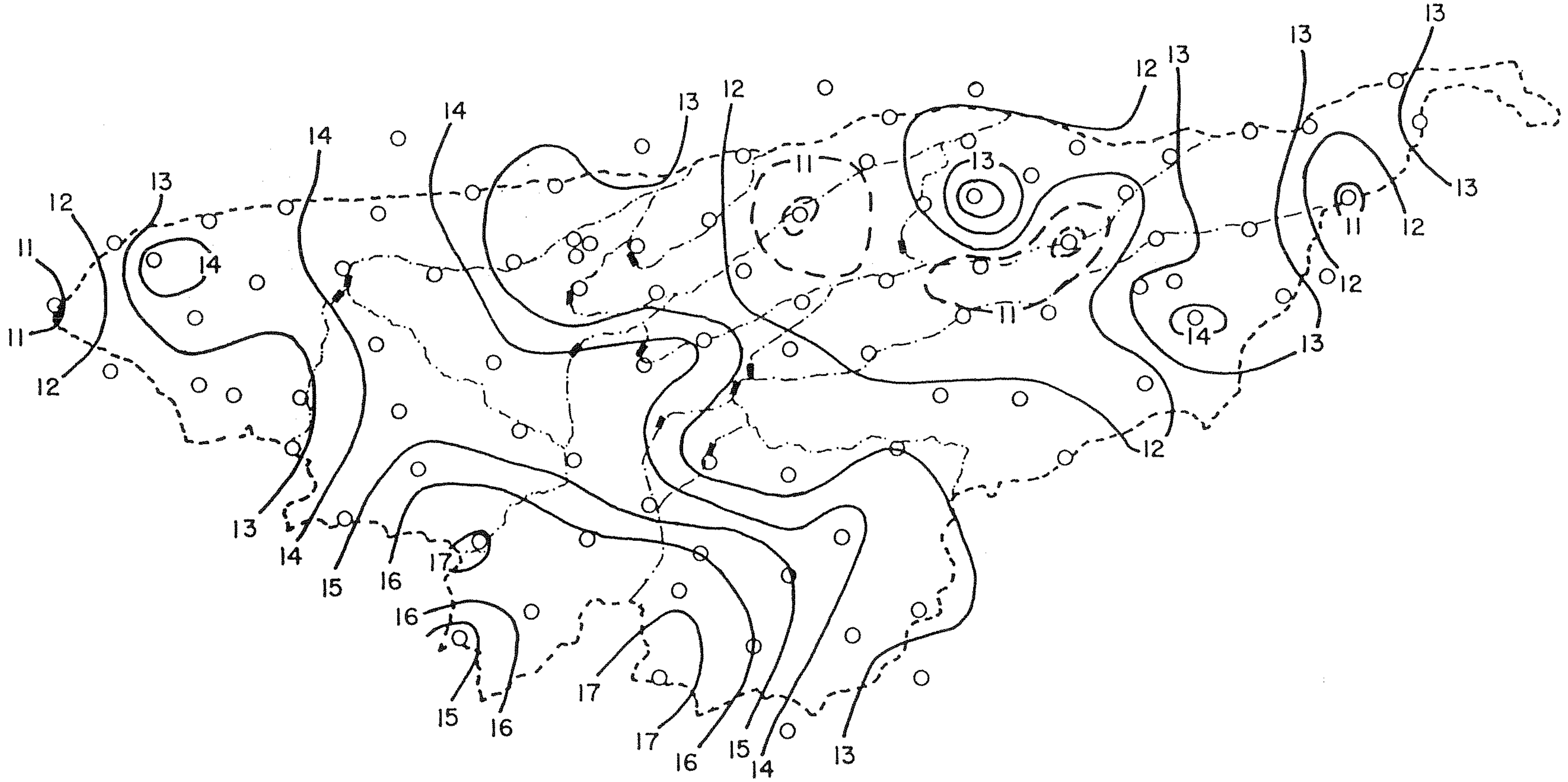


Figure 5.--Isoheytal map of annual precipitation for 1968 on Walnut Gulch watershed.

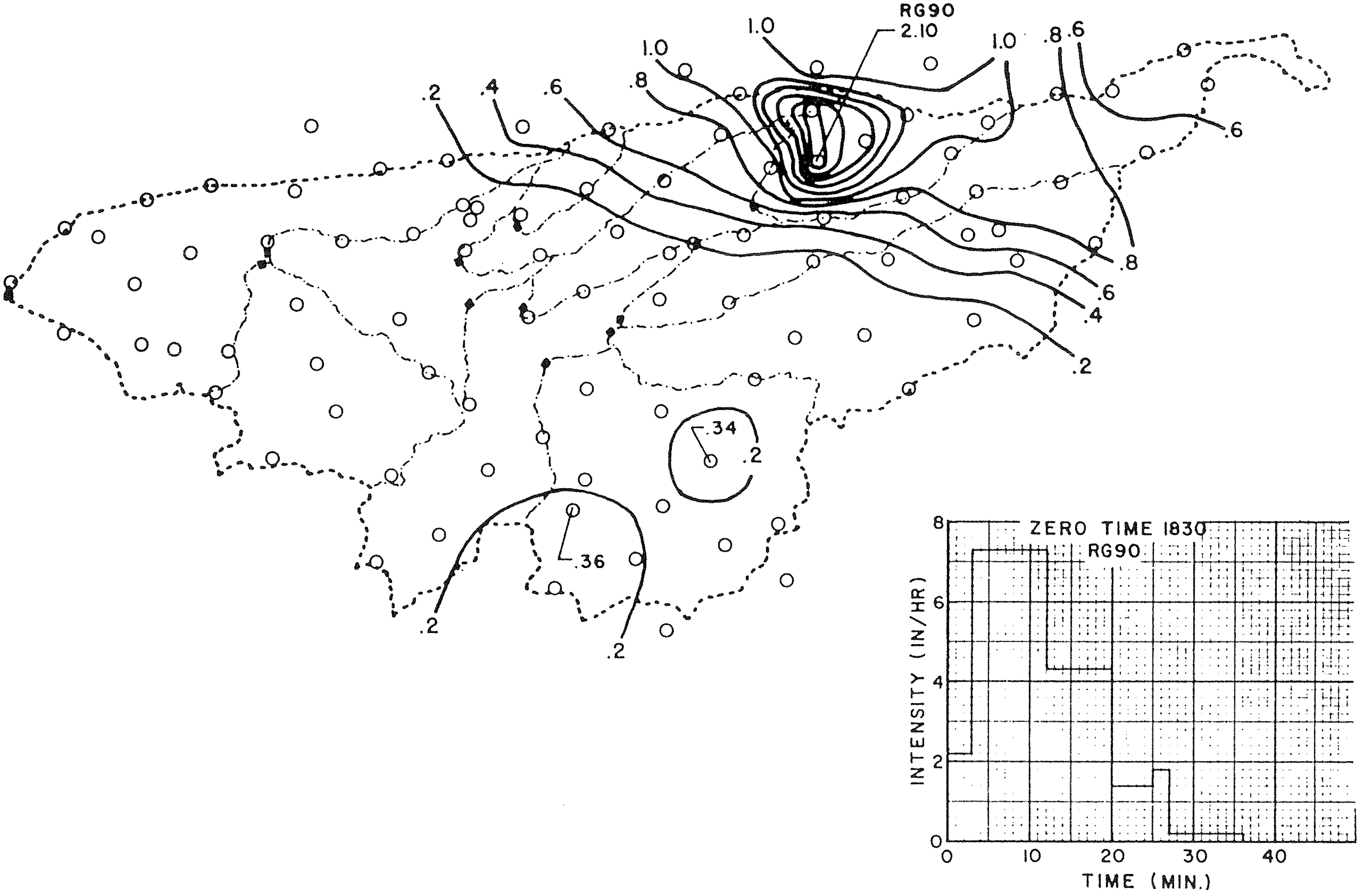


Figure 6.–Isohyetal map of total storm depth for the event on August 5, 1968, on the Walnut Gulch watershed.

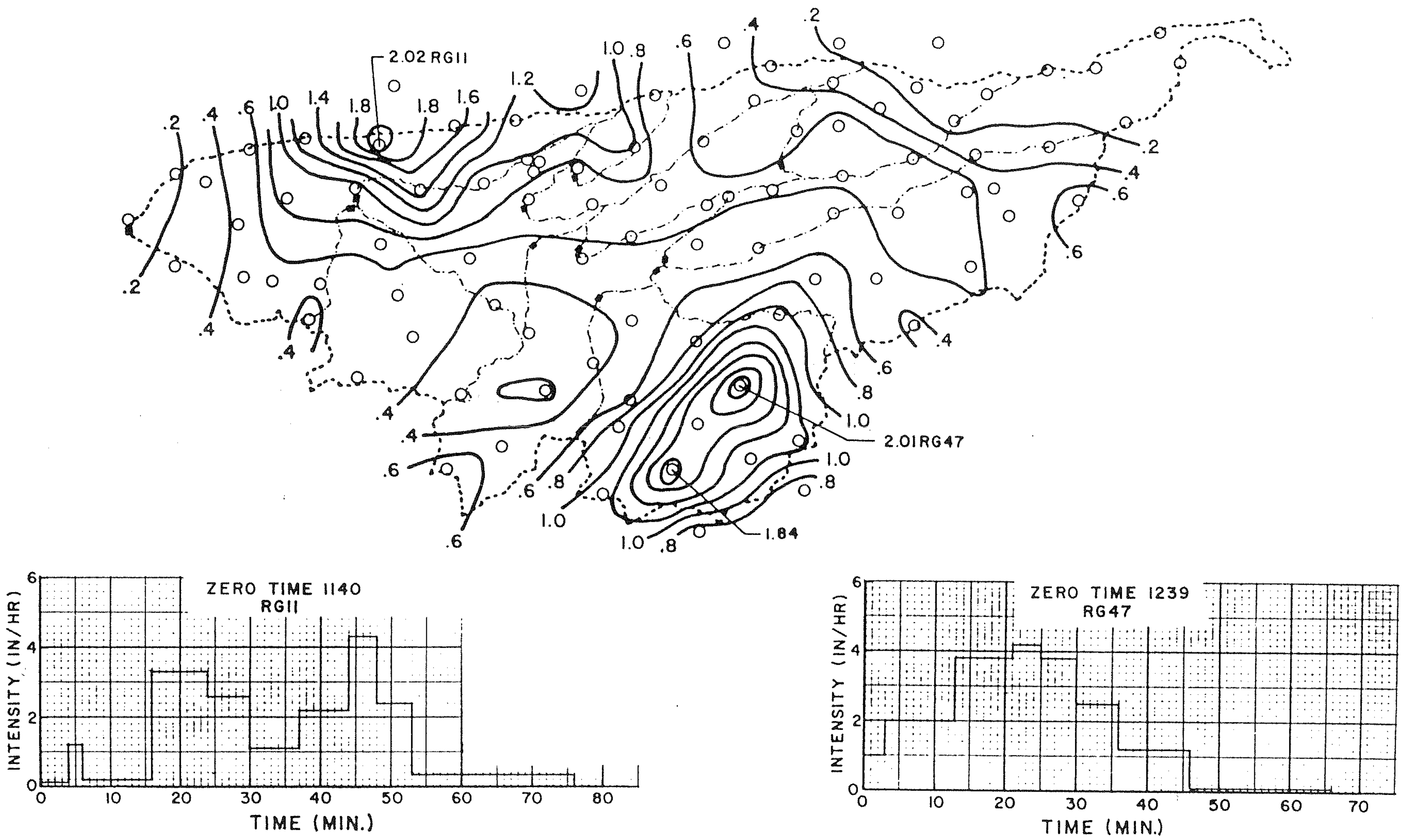


Figure 7.–Isohyetal map of total storm depth for the event on August 31, 1968, on the Walnut Gulch watershed.

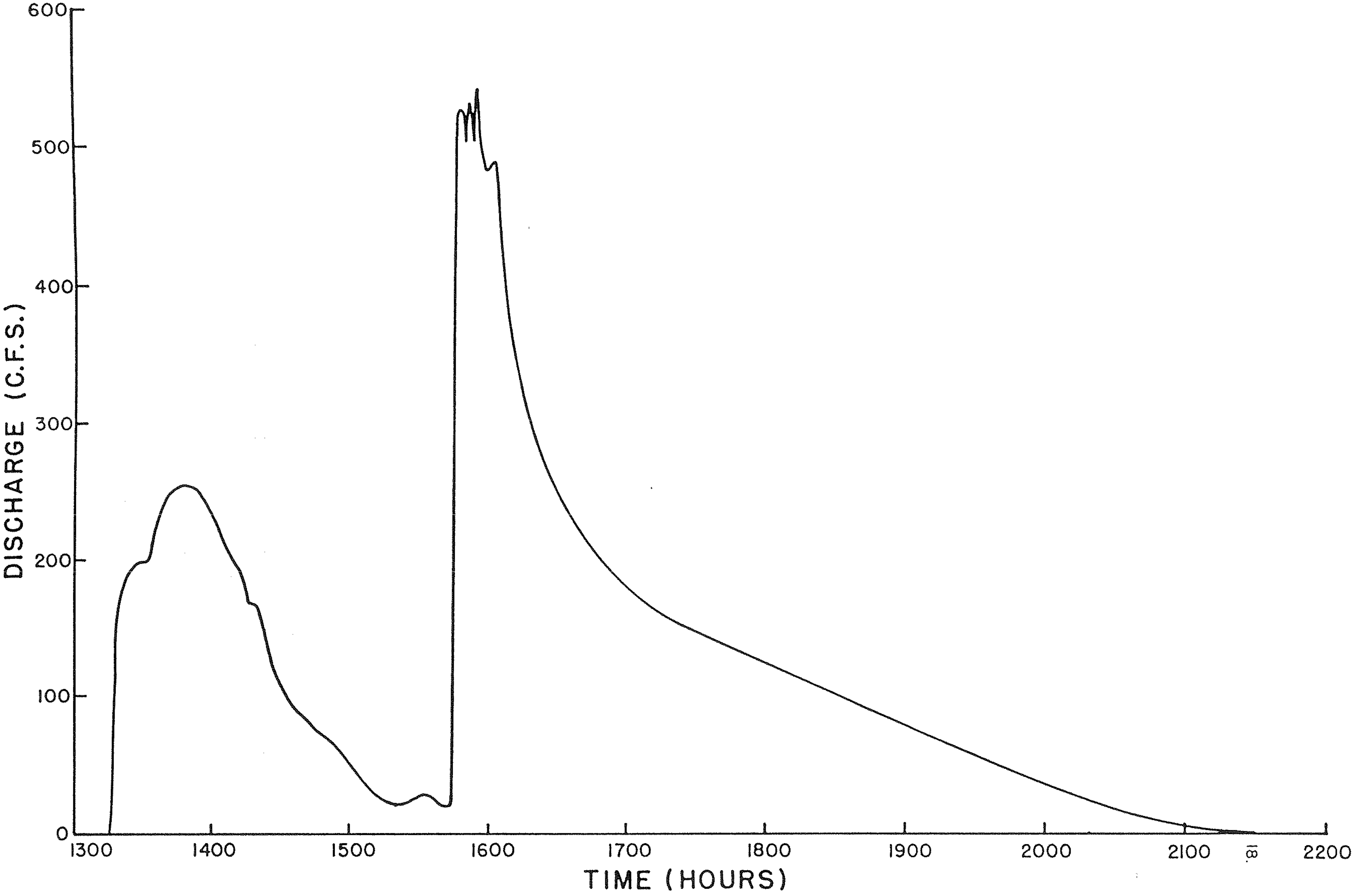


Figure 8.—Flume 1 runoff hydrograph on the Walnut Gulch watershed for the event of August 31, 1968.

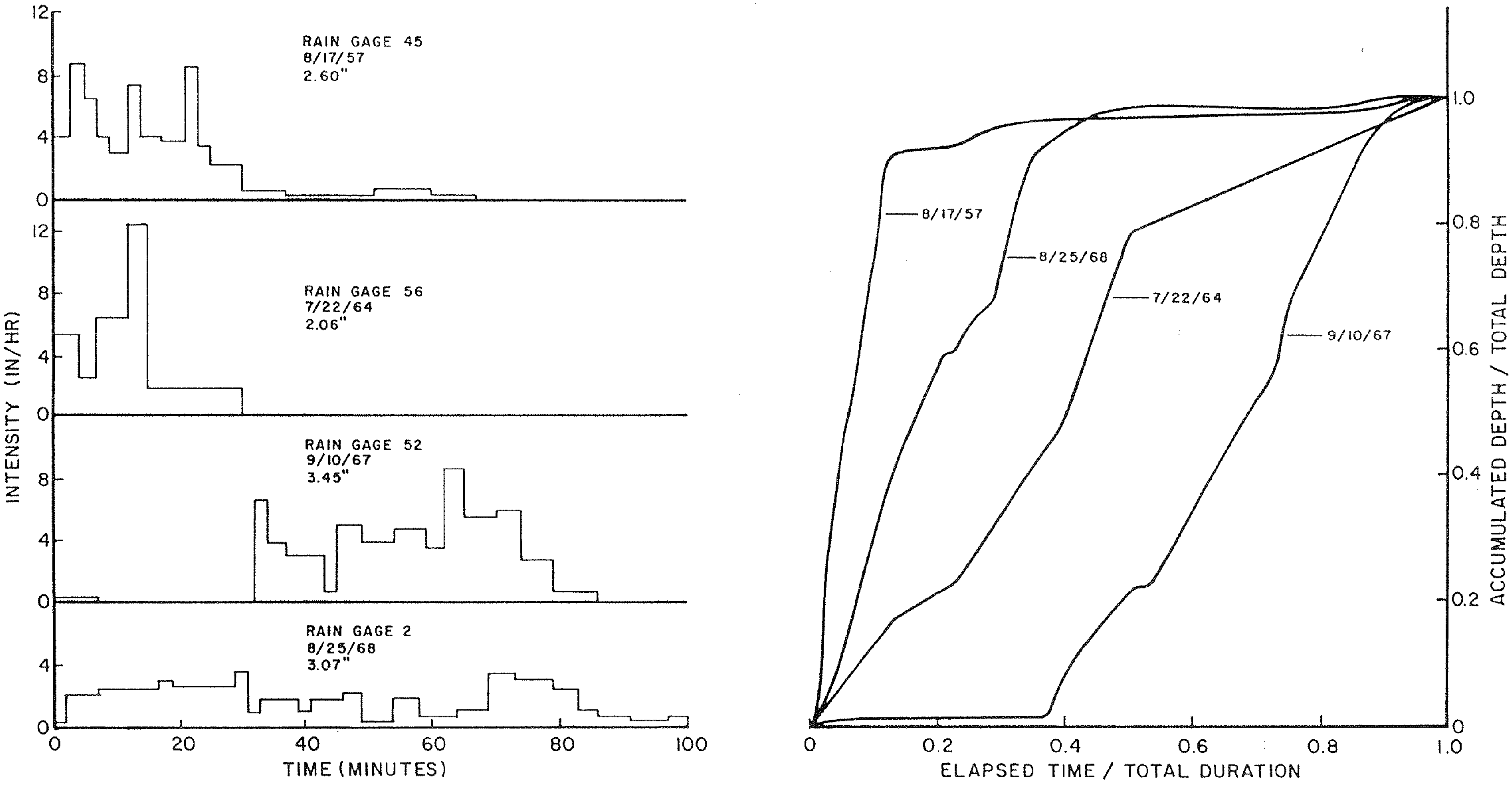


Figure 9.—Precipitation hyetographs and distribution graphs for selected storms on the Walnut Gulch watershed.

TABLE 1.–*Maximum precipitation amounts in storms of selected duration*

Watershed and date	Rain gage No.	Maximum amounts in inches for duration in minutes								
		2	5	10	15	20	30	60	120	360
Walnut Gulch:										
8/25/68	2	0.12	0.28	0.53	0.73	0.94	1.30	1.98	3.03	
9/10/67	52	.29	.61	1.07	1.43	1.82	2.48	3.42	3.45	
7/22/64	56	.41	.83	1.23	1.62	1.77	2.06	2.06	2.06	
8/17/57	44	.29	.58	.92	1.31	1.77	2.28	2.45	2.53	
Alamogordo Creek:										
6/5/60	34	1.42	2.02	2.54	2.91	3.22	3.54	3.88	3.96	4.07
6/16/66	34	.38	.77	1.36	1.83	2.21	2.96	3.49	3.79	3.98
8/21/66	61	.41	.73	1.22	1.64	1.98	2.43	3.58	4.55	5.02

problems of variable channel density and variable soil-vegetation complexes in natural watersheds, we installed 6- by 12-foot plots to study rainfall-runoff relationships.

Stepwise multiple regression analysis of plot data showed that average runoff for any one location-year increased as the precipitation quantity increased; decreased as the crown spread of vegetation increased; and increased as antecedent soil moisture increased (22). These independent variables accounted for 72, 3, and 0.5 percent of the variance in the runoff prediction equation developed. The antecedent moisture experiment was planned so that one-third of the plots remained untreated, while the remaining two-thirds received additional moisture at two levels. Three fertility levels were also incorporated statistically into the experiment. Agronomic results of the fertilizers and additional moisture were dramatic on some of the combinations (fig. 11). The research demonstrated a type of range improvement that might be achieved with weather modification. An additional 2 to 4 inches of rainfall during the summer growing season would undoubtedly increase the forage yield manyfold. The effects of these modifications on the ecological and hydrological balances in a watershed must also be examined. The runoff prediction equation developed showed that increasing crown spread and basal area of the vegetation reduced the runoff generated on the plots. The consequences of reduced runoff at a downstream location must also be evaluated.

In another portion of the watershed, range improvement treatments–brush clearing, pitting, and grass seeding–were applied to runoff plots in a randomized factorial arrangement (11). Little correlation between the treatments and surface runoff was found, but brush clearing appeared to increase the rain-site runoff, and the grass seeding appeared to reduce it. As the crown cover increased, surface runoff decreased significantly. Although pitting greatly increased surface roughness, it had little effect on runoff after the first few storms, which smoothed the pits and reduced their storage potential.

Kincaid, Gardner, and Schreiber (10) showed that infiltration on Walnut Gulch was variable and related to a number of site characteristics. Correlation was good between the time required to infiltrate 0.50 inch of water and the percentage of the plot area covered by vegetation, litter, and the erosion pavement. Their data summarized six representative infiltrometer runs from 20 tests, using a Type F infiltrometer. Further analysis of these data showed a good correlation between the initial, final, and average 60-minute infiltration rates and the canopy of shrubs and half-shrubs, combined with the ground cover of grasses, litter, and the erosion pavement. The regression equation for each line in figure 12 shows that infiltration is strongly associated with plot cover. This result further verifies the plot studies previously discussed. Most of the variation in the plot cover was associated with a crown spread of 5.7 to 43 percent for shrubs and half-shrubs. The basal area of grasses and of litter increased when the crown spread decreased and vice versa.

Very small watersheds are useful when studying rainfall-runoff on individual soil-vegetation complexes, because precipitation can usually be assumed to be constant over the area. Osborn and Lane (18) used stepwise multiple linear regression to predict five runoff variables (total volume, peak rate, duration, rise time, and lag time) on four small brush-covered watersheds (0.56 to 11.0 acres) on Walnut Gulch. The independent variables were eight precipitation variables, two state variables (antecedent moisture indicies), and three watershed variables (area, average slope, and length). When the data from each watershed were treated separately, the total storm precipitation was the principal variable for determining the runoff volume and accounted for between 76 and 89 percent of the variance. When the data were combined for the four watersheds, the maximum 15-minute precipitation amount became the

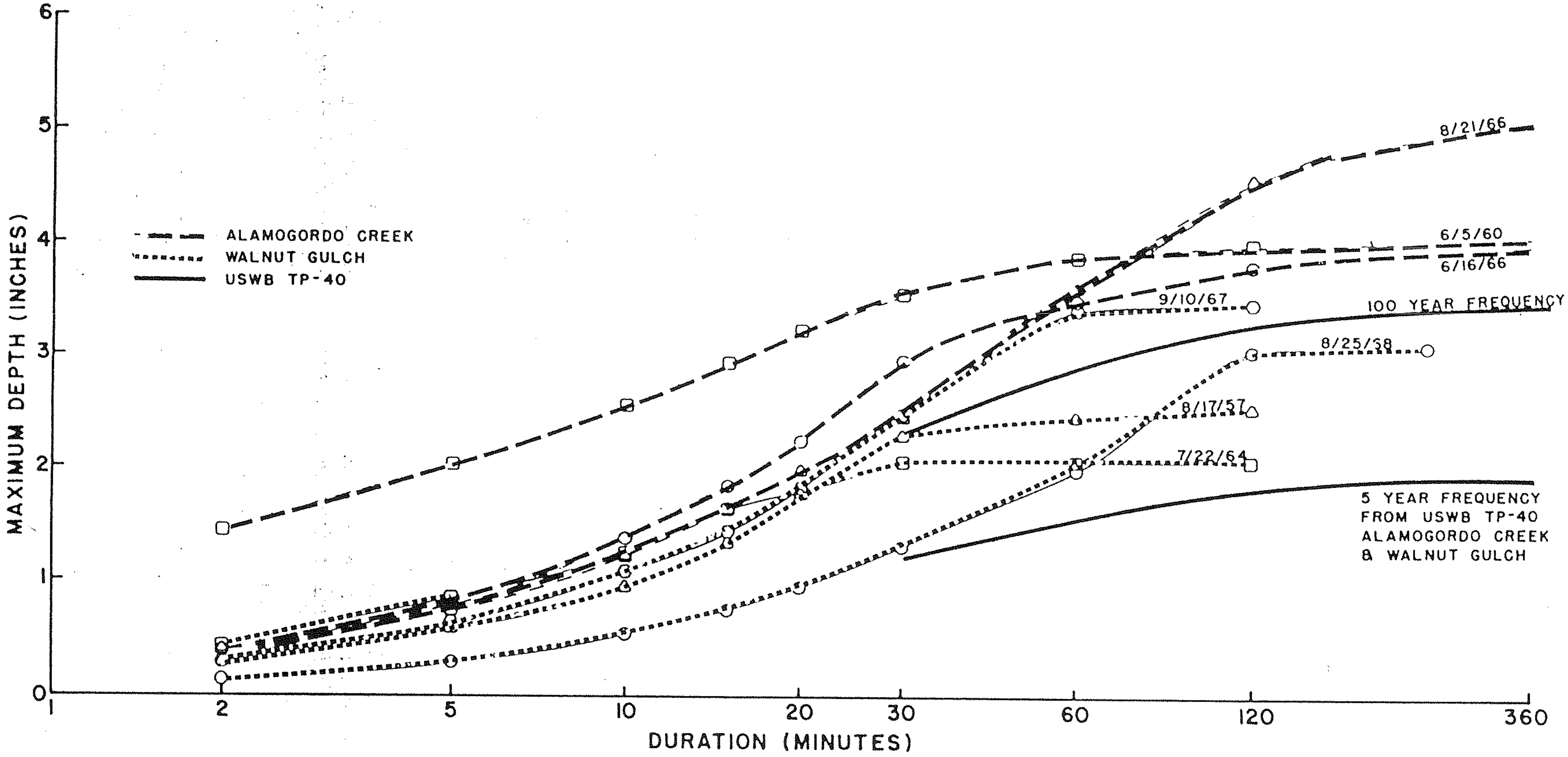


Figure 10.–Maximum point precipitation amounts versus duration for selected storms on the Walnut Gulch and Alamogordo Creek watersheds.

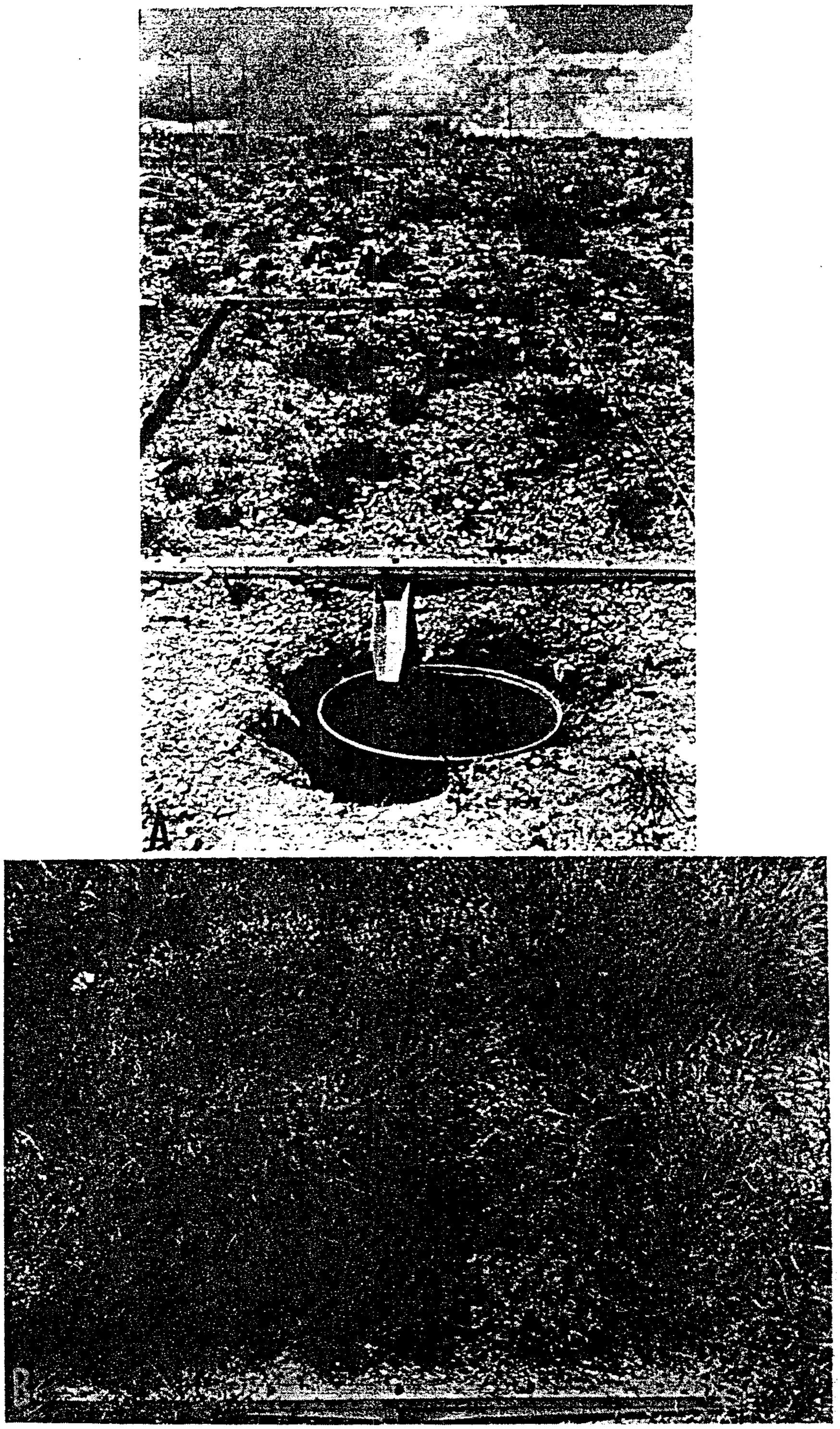


Figure 11.–*A*, A 6- by 12-foot plot on August 8, 1963, after a metal border and a collecting trough had been installed; runoff measured in the volumetric tank at the lower end. *B*, The same plot on August 24, 1964, depicting agronomic response with about 4 inches of supplemental moisture each season, plus a fertilizer application of 80 pounds of N and 80 pounds of P per acre.

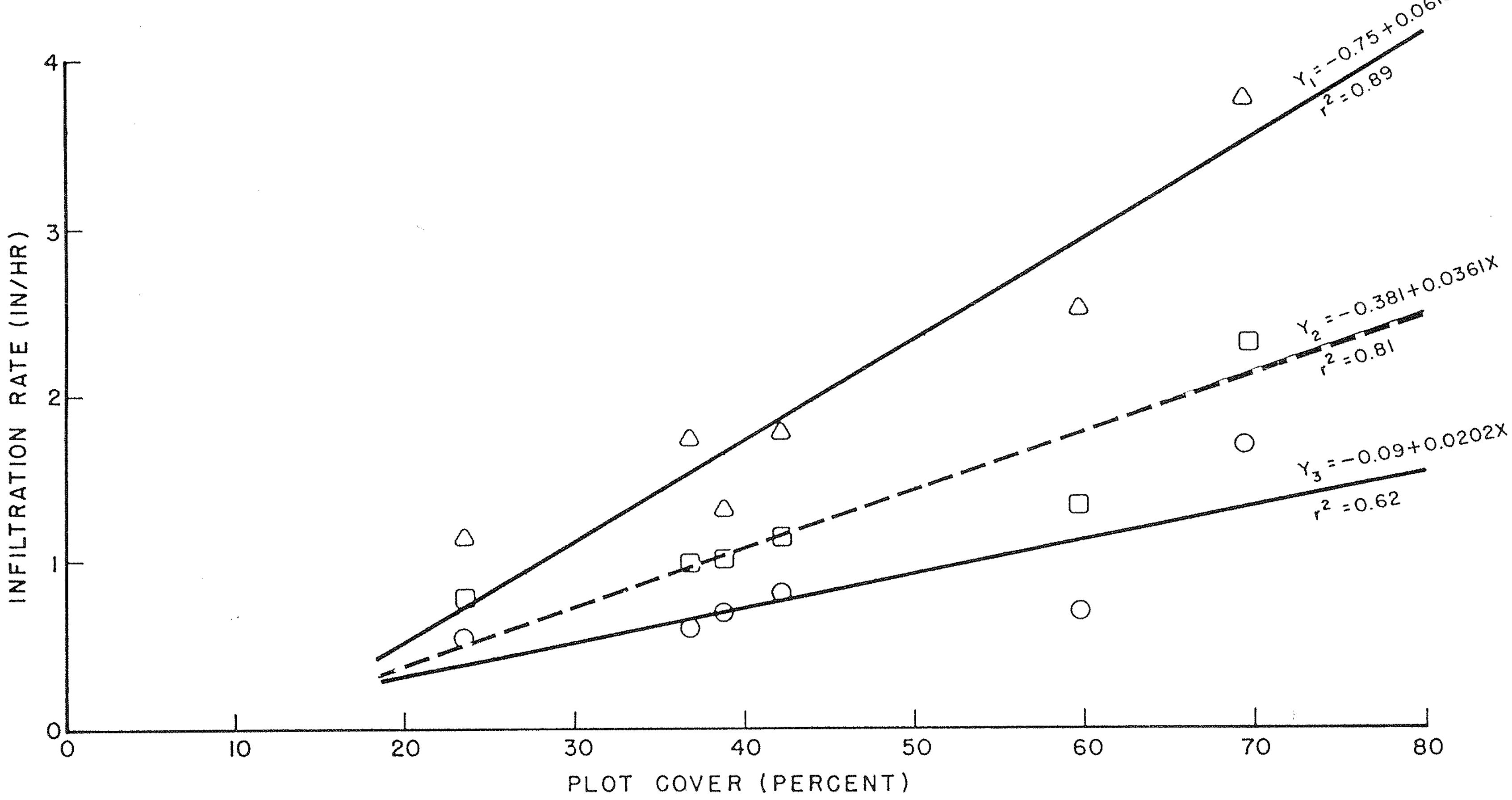


Figure 12.–Infiltration rate for first 0.50 inch of infiltration (Y_1), average rate for the first hour (Y_2), and rate after 60 minutes (Y_3) versus the canopy of shrubs and half-shrubs combined with the ground cover of grass, litter, and erosion pavement.

dominant variable for determining both the volume and peak rate of runoff. The runoff duration was best predicted by the maximum 10-minute precipitation and watershed slope, but only 40 percent of the variance was explained by these variables. Rise time and lag time were not successfully related to the independent variables in this study.

Two of the four unusual precipitation events discussed previously centered above instrumented stock watering ponds (ponds behind earthen dams) and produced large rates and volumes of runoff. The September 10, 1967, storm produced a peak discharge estimated at more than 1,500 c.f.s. per square mile from the 84-acre drainage and resulted in 2.6 inches of runoff from the area (75 percent of the storm rainfall) (19). The August 25, 1968, storm on the lower portion of Walnut Gulch produced an exceptionally large flow from a 58-acre watershed. Because of the longer duration and lower intensity (see hyetograph in fig. 9), the estimated peak discharge exceeded 1,300 c.f.s. per square mile with 2.0 inches of storm runoff (65 percent of the storm rainfall).

It is difficult to determine the frequency with which precipitation events of this magnitude and producing this volume and peak rate of discharge could be expected on any portion of Walnut Gulch. The storms measured at the stock tanks occurred in the second and third years of record. Based on the short record from these tanks and other parts of Walnut Gulch, storms of this magnitude or greater could be expected on some part of the 58-square-mile watershed roughly once every 4 years.

Transit Phenomenon

Transmission losses are one of the most important factors in evaluating ephemeral streams such as Walnut Gulch. Stream channels are dry except when geologic anomalies force subsurface flow to the surface, or except for brief periods following thunderstorms. On Walnut Gulch, most measuring stations are dry more than 99 percent of the time, with only five to 15 runoff events each year. The large volume of coarse-textured, high-porosity alluvium in the channels significantly reduces the volume of the runoff as it moves through the channel system. Many researchers have documented transmission losses, but success in modeling the phenomenon has been limited (1, 2, 9, 13, 21, 24).

Runoff is difficult to measure in ephemeral streams. An early effort in our watershed research program involved designing and building suitable measuring structures to provide a satisfactory hydraulic control while allowing the high sediment and debris loads to pass through the structure. Conventional current metering stations were impractical because of the extremely high point velocities (up to 20 feet per second) and the rapidly changing stages. Following hydraulic model studies at the Water Conservation Structures Laboratory at Stillwater, Okla., the first Walnut Gulch prototype supercritical measuring flume (fig. 13) was completed in 1958 (4). Field observations of this and later flumes have indicated satisfactory field performance and close comparison with the laboratory structures (17).

The runoff-measuring network has been expanded to 11 such flumes (fig. 14). These flumes isolate seven

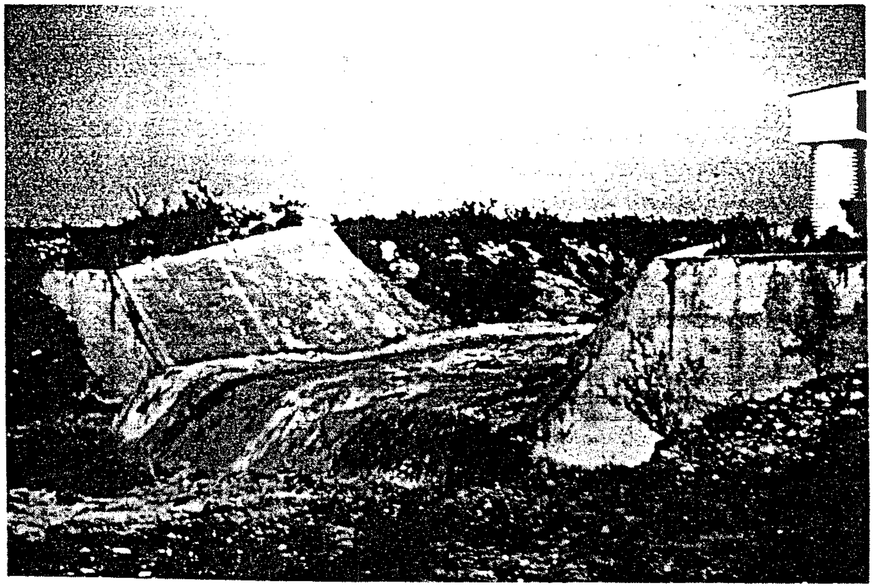


Figure 13.–A 1,000-c.f.s. flow in flume 11 on July 30, 1966, at Walnut Gulch. This structure, with a design capacity of 5,500 c.f.s., often has flows with suspended sediment loads of 50,000 p.p.m.

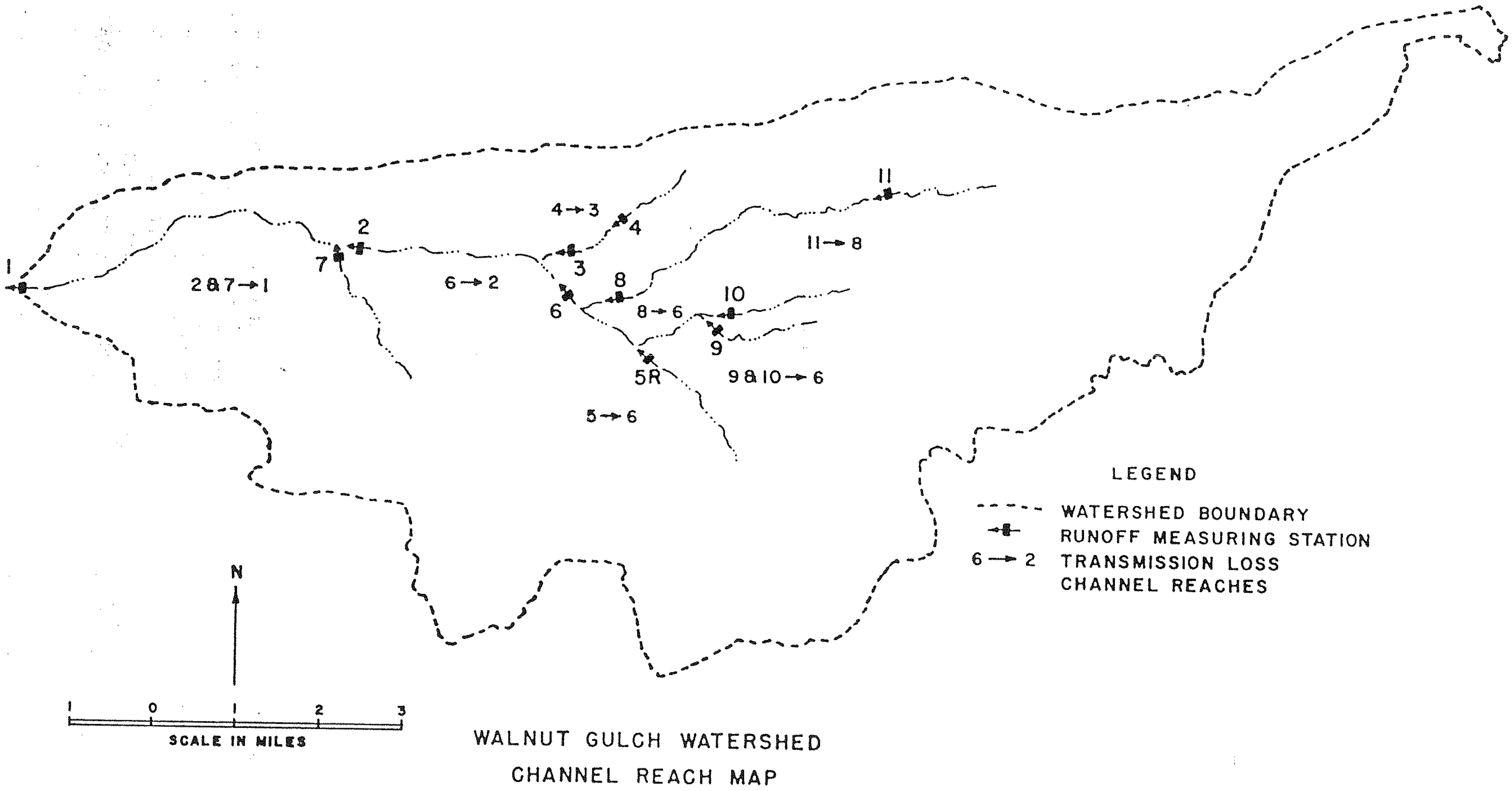


Figure 14.–Instrumented channel reaches on the Walnut Gulch for which transmission losses can be evaluated.

channel segments where the transmission loss magnitude can be measured by comparing the measured hydrographs at the upstream and downstream stations of a channel reach for storm events with all runoff originating above the upper station. Table 2 summarizes data on the length and width of these channels. This variability in the characteristics of the instrumented channels allows mathematical modeling of the transmission loss phenomenon.

TABLE 2.–*Transmission loss channel reaches, Walnut Gulch experimental watershed*

Channel reach	Channel length	Average channel width for "in-bank" flow
	Miles	*Feet*
7 and 2 ——> 1	4.0	217
6 ——> 2	2.8	160
8 ——> 6	0.9	68
11 ——> 8	4.0	43
5 ——> 6	1.5	63
4 ——> 3	1.2	36
9 and 10 ——> 6	2.7	57

The isohyetal map of figure 6 and the hydrographs of figure 15 show an example of a runoff event with the precipitation limited to a portion of the study area. Most of the runoff for this August 5, 1968, storm originated above flume 11 (fig. 6). The 27.40 acre-feet of runoff with a peak discharge of 1,080 c.f.s. at flume 11 was reduced to 12.85 acre-feet with a peak discharge of 421 c.f.s. at flume 8. (Limited tributary inflow on this event would result in a larger value for the 14.55 acre-feet of transmission loss.) The runoff was further reduced in the 0.9 mile of channel between flumes 8 and 6 to a peak discharge of 313 c.f.s. and only 9.28 acre-feet of runoff. Only a trace of runoff was measured at the outlet of Walnut Gulch for this runoff event. The 14.55-acre-foot transmission loss for this event was not particularly large compared with the nearly 82 acre-feet of water lost for the September 11, 1964, storm for this same channel reach. The runoff volume at flume 8 is related to the volume at flume 11, decreased by an amount related to the antecedent moisture level of the channel (12). Transmission losses on other channel segments have been estimated to approach 80 acre-feet per mile depending on the anticipated maximum discharge.

The magnitude of transmission losses for any flow event is extremely variable, but seems to be related to (1) flow duration, (2) channel length and width, (3) antecedent moisture conditions, (4) peak discharge, (5) flow sequences, (6) volume and characteristics of the alluvium, and (7) amount of clay in suspension in the runoff.

In ephemeral stream channels, transmission losses affect surface water yield. The surface water yield per unit area decreases with increasing drainage area on Walnut Gulch (fig. 16). A similar relationship was found by Keppel (7) for the Santa Cruz basin near Tucson, Ariz., although the rate of decrease was greater.

"On-site" runoff (precipitation excess) on Walnut Gulch may average about 2 inches per year, but the net surface outflow from the entire basin is only about 1/4 inch per year (fig. 17). This loss of 1.75 inches per year as the runoff moves in the channel system represents the transmission loss magnitude for the 58-square-mile area. Only 10 to 15 percent of the precipitation excess appears as surface runoff at the watershed outlet.

Stream channel management may increase water supply in arid and semiarid areas. In some channel segments, much of the transmission loss water is not available for beneficial uses because of evaporation from the streambed and transpiration of riparian vegetation. When the underlying geology is such that impervious layers beneath the channel limit the downward movement of water, recharge to the regional groundwater is low. Holding the transmission loss water in perched or local temporary aquifers increases the evaporation rate. When the storage potential of the aquifers supplied from transmission losses is satisfied (a common occurrence late in the runoff season), the runoff moves downstream undiminished in volume. The management of the vegetation that receives moisture from the temporary aquifers and is generally found adjacent to stream channels requires additional study.

In some channel reaches, the tremendous volumes of alluvium provide a large immediate reservoir for the transmission loss water, and groundwater recharge occurs as the water moves under the force of gravity. Such a condition exists near the outlet of Walnut Gulch where the water table is about 150 feet beneath the channel bed (fig. 18). In past years, the hydrograph for a well in the stream channel has responded erratically to flows (25). The 15-foot rise in regional water level, beginning August 20, 1966, probably results from moisture movement through the channel alluvium. A mounding on the regional water table is followed by a decline as the mound dissipates, leaving a slight increase in the water level. Similar hydrographs have been observed in 3 of the past 6 years and appear to be related to the amount of surface runoff in the channels at this location or to the magnitude of the transmission losses.

Transmission losses are undoubtedly the primary groundwater recharge source in limited rainfall areas. Rainfall infiltration is limited in upland areas. On Walnut Gulch, soil moisture has not been noted below 5 feet except where the water accumulates (as in grass swales). Thus, recharge from stream channels is the primary recharge mechanism. Using geophysical techniques, Wallace and Spangler (26) estimated that 2.5 million acre-feet of groundwater were stored in the deep alluvial portion of Walnut Gulch (fig. 19). This volume of

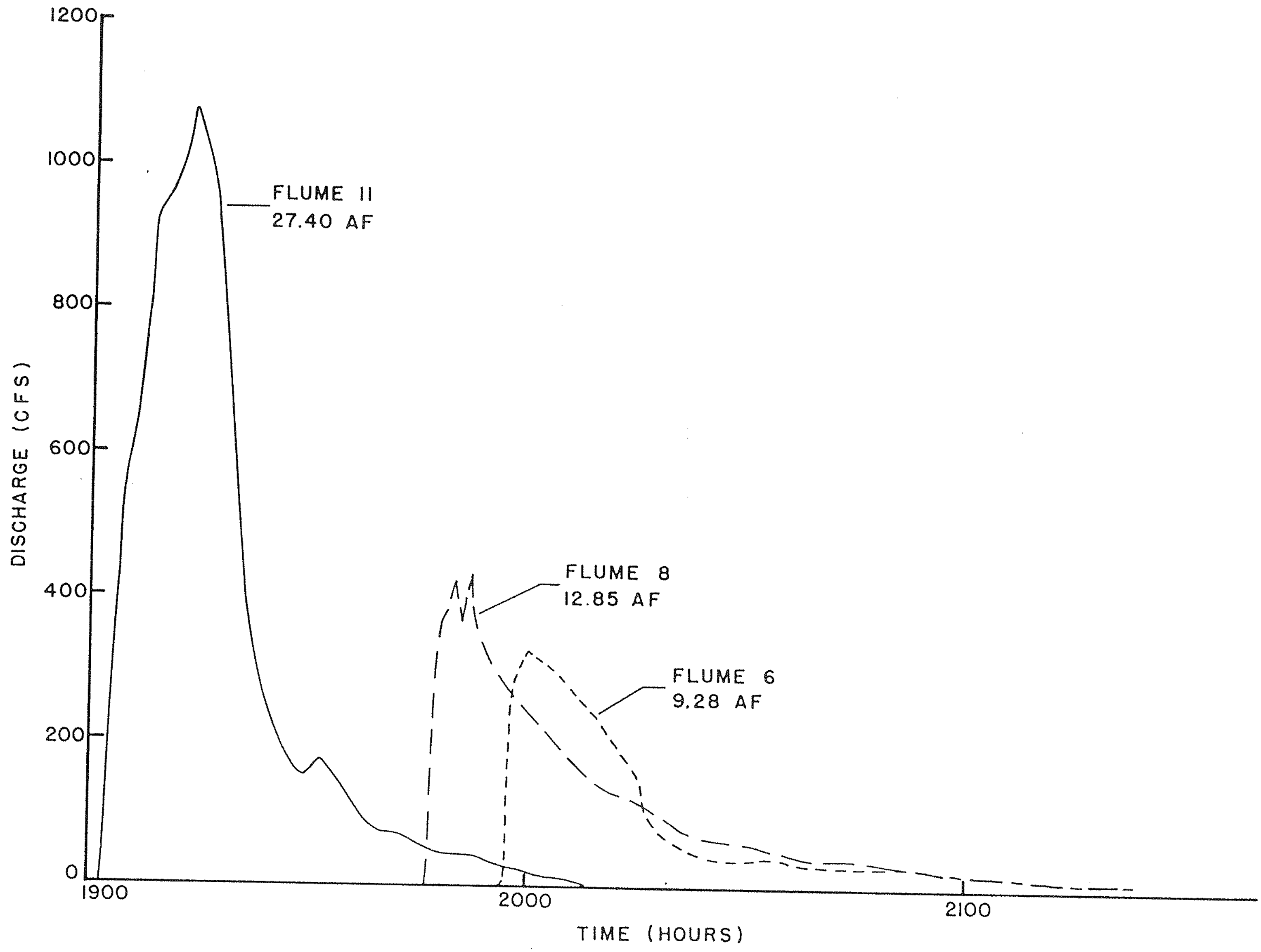


Figure 15.–Runoff hydrographs for selected flumes on the Walnut Gulch watershed for the event of August 5, 1968.

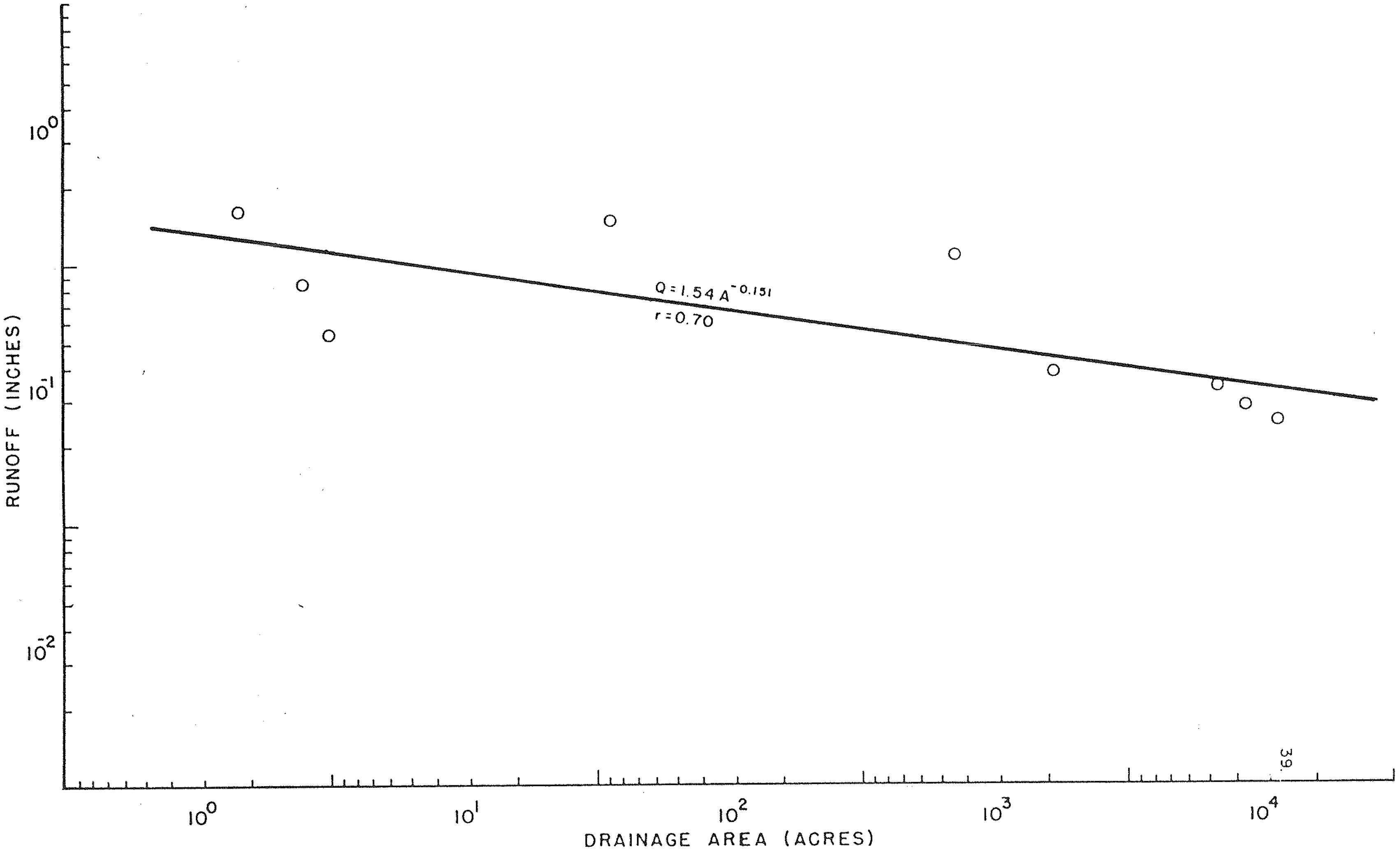


Figure 16.—Runoff versus drainage area for the Walnut Gulch watershed.

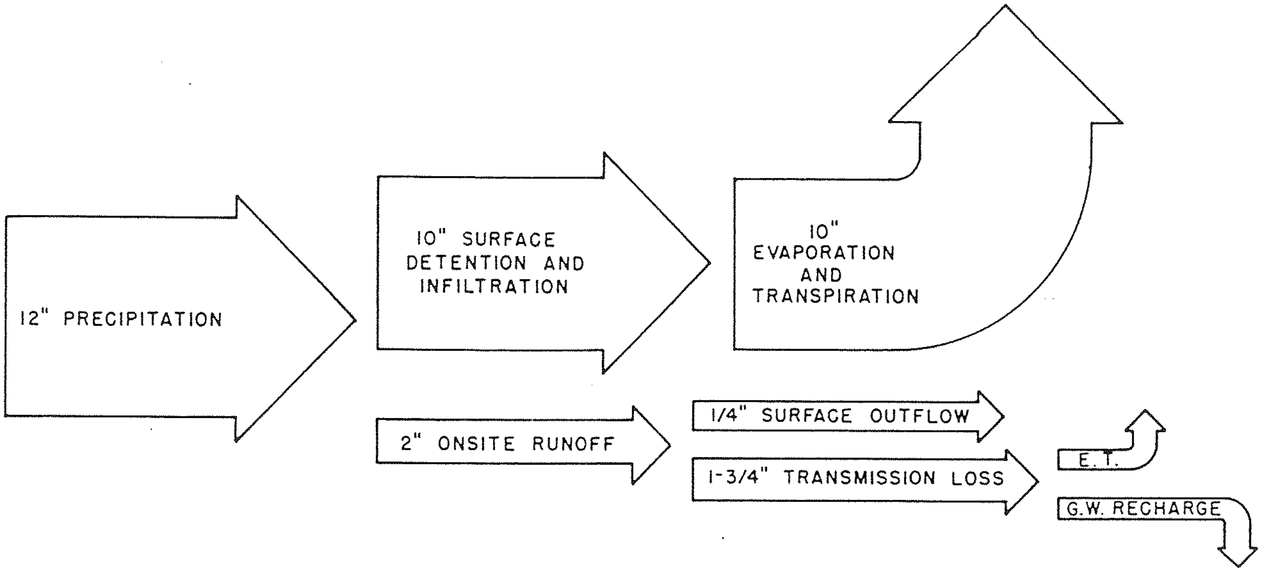


Figure 17.–Water balance of Walnut Gulch watershed.

groundwater is much greater than the estimated 5,400-acre-foot annual transmission loss of Walnut Gulch. Assuming that one-half of the transmission loss water becomes recharge to the regional water table, the volume in storage is 1,000 times the recharge. The tremendous storage volume represents recharge from (1) outside the surface boundary of Walnut Gulch; (2) periods when the recharge was greater than at present; and (3) the accumulation of recharge over a long period.

Streambed treatments to enhance or inhibit transmission losses based on known groundwater recharge characteristics need further investigation. For example, the surface water yield of Walnut Gulch could be increased by about 90 percent by sealing the lower 6.8 miles of the main channel, and could be increased by about 67 percent by sealing only the lower 4 miles of the main channel. However, such channel sealing might increase the downstream flood damage potential because transmission losses generally decrease the peak discharge in addition to the flow volume. Therefore, channels would have to be sealed where greater peak discharges would not cause flooding. These channel treatments should probably entail sealing tributary channels and increasing the infiltration of main channels.

Summary

The hydrology of semiarid areas in the Southwestern United States is characterized by (1) high intensity, limited areal extent precipitation, (2) limited soil moisture, (3) sparse vegetation, (4) high evaporation, (5) high transmission losses, and (6) low annual surface water yield. The surface water yield per unit area decreases rapidly with increasing watershed area as a result of the transmission losses.

In studies such as those on Walnut Gulch, we must consider the interrelation of erosion and sediment movement in semiarid watersheds and the watersheds' yields of water. The water yield of these semiarid areas is greatly affected by sediment deposition in the channels of the watershed as well as in the channels on the major streams to which the watershed may be tributary. Erosion control and control of sediment movement into major tributary channels from semiarid watersheds are very important to sustained downstream water supplies, as well as to the sustained capability of semiarid rangelands to produce forage.

Stream channel management with land management may provide needed future water supplies for the arid and semiarid regions. The causes and effects of these programs might not be presently known, and some of these programs might not be economically feasible today. But they may be feasible in the near future, and research such as that described here may provide the needed planning tools for optimizing water and land resource uses. A combination of land surface management to enhance infiltration and increase forage production, combined with stream channel management involving both channel sealing and selective infiltration enhancement in some channels, will optimize water use, provide additional forage, and provide water downstream.

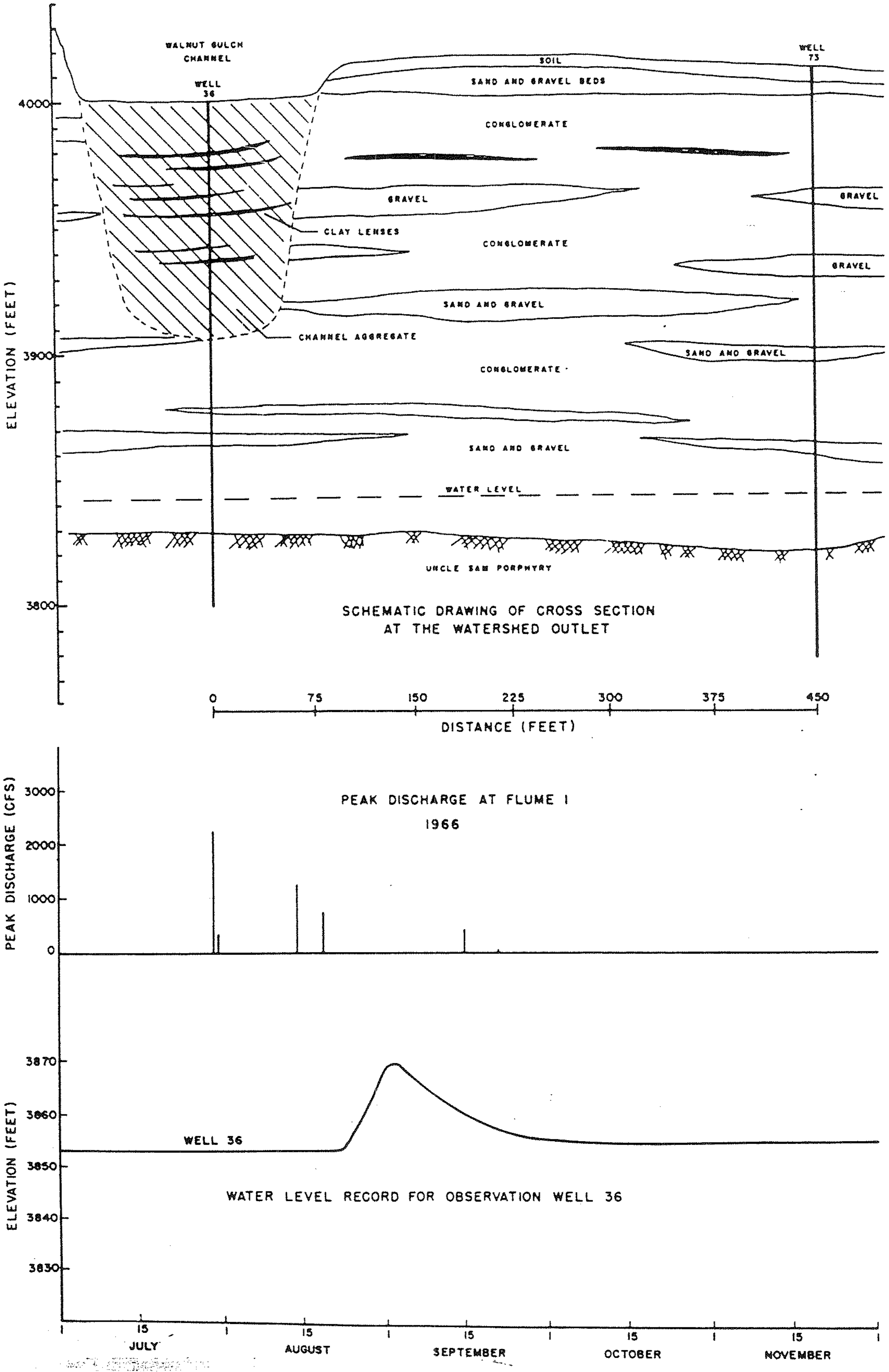


Figure 18.—Groundwater hydrograph, peak discharge in the channel, and a schematic cross section at the outlet of Walnut Gulch.

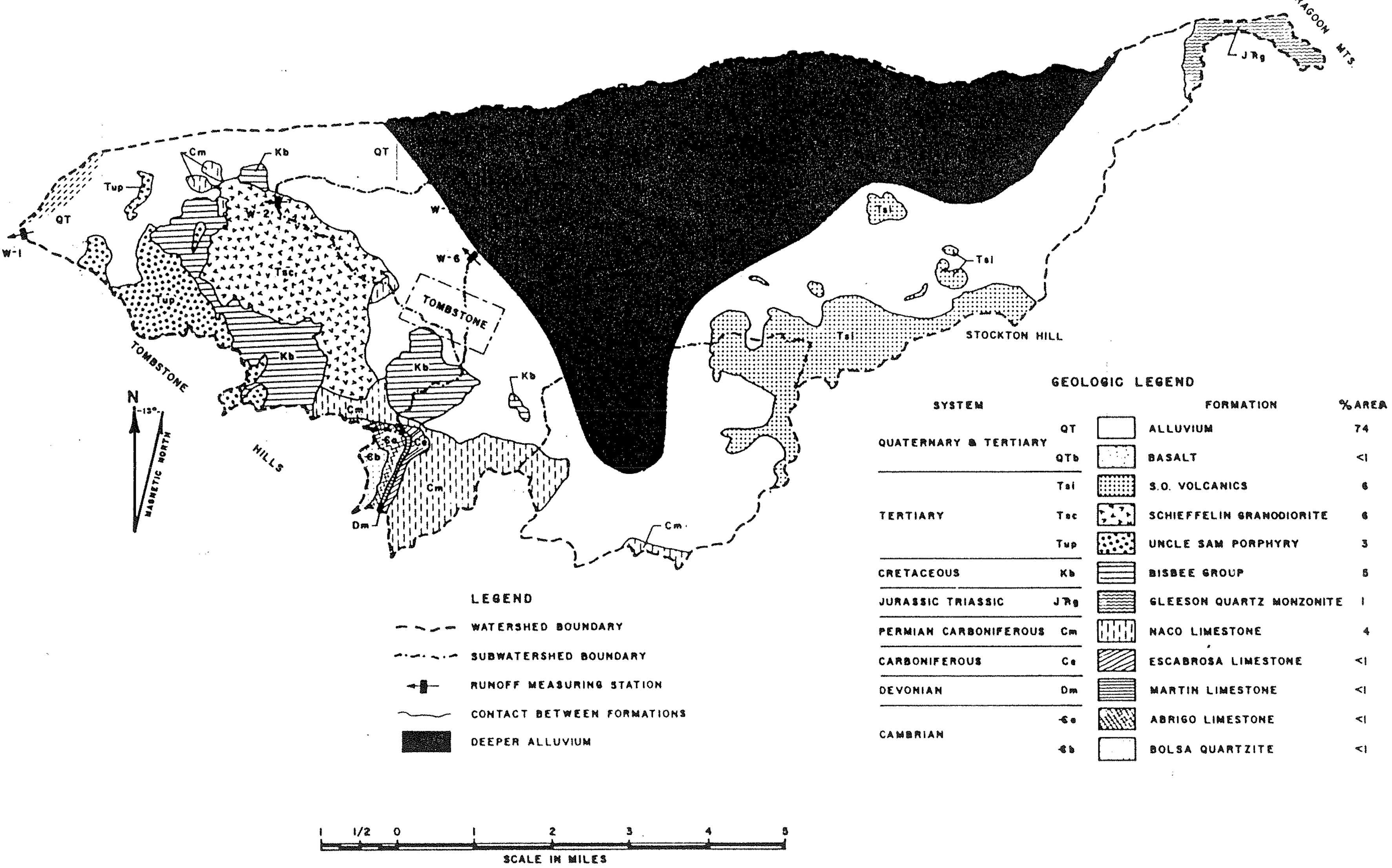


Figure 19.–Deep alluvial areas of Walnut Gulch that underlie 54 percent of the surface area are estimated to contain 2.5 million acre-feet of groundwater at depths up to 3,200 feet.

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