#94

# THUNDERSTORM RUNOFF ON THE WALNUT GULCH EXPERIMENTAL WATERSHED, ARIZONA, U.S.A. *

H. B. OSBORN and K. G. RENARD **

SUMMARY

The Southwest Watershed Research Center of the Agricultural Research Service operates the 58-square-mile (148 km2) Walnut Gulch Experimental Watershed in southeastern Arizona. This watershed is fairly representative of several hundred thousand square miles of mixed grass and brush rangeland in the Southwestern United States. Rainfall and runoff records have been collected from the watershed since 1954. The present network contains 95 weighing-type recording rain gages and 21 permanent runoff measuring stations.

About 70 percent of the average annual precipitation of 11.5 inches (29.2 cm), and almost all runoff, occurs in the summer thunderstorm season from June through September. Rainfall variability in time and space dominates any rainfall-runoff relationship, especially on the smaller subwatersheds (up to several square miles in area). Flow abstractions in the normally dry ephemeral channels become increasingly important with increasing watershed size. Whereas onsite runoff may average 20 to 25 percent of summer rainfall, runoff from the 58-square-mile (148 km2) watershed averages only about 4 percent of the summer rainfall. Correlation between Thiessen-weighted rainfall and runoff for individual events decreases with increasing watershed size because of the limited areal extent of thunderstorm rainfall and because of the increasing magnitude of channel abstractions for the larger watersheds.

The effects of transmission loss on the channel flows, as represented by changes in hydrograph shape, height, and volume, are being studied. Outflow hydrographs have been predicted for a 4-mile (6.4 km) reach of Walnut Gulch, with no tributary input, using regression techniques and a three-parameter gamma distribution. This work is being expanded to include other channel reaches with varying physical dimensions.

The "key gage" principle is not satisfactory for the Walnut Gulch watershed for representing either storm or annual runoff. Peak discharges have been highest following relatively dry periods, which is probably not coincidence. The larger thunderstorms have followed dry periods when convective heating of the ground surface is possible because of less cloud cover and drier surface conditions.

RÉSUMÉ

*ÉCOULEMENT D'ORAGE SUR LE BASSIN EXPÉRIMENTAL DE WALNUT GULCH EN ARIZONA*

Le Centre de Recherches sur bassins du Sud-Ouest de l'ARS conduit les recherches sur le bassin de 58 milles carrés (148 km$^2$) de Walnut Gulch dans le Sud-Ouest de l'Arizona. Ce bassin est assez bien représentatif de plusieurs milliers de milles carrés de terrains couverts d'herbes ou de buissons dans le Sud Ouest des États-Unis. Les précipitations et l'écoulement ont été relevés sur ce bassin depuis 1954. Le réseau actuel comprend 95 pluviographes à pesée et 21 stations de jaugeage permanents.

Environ 70% de la précipitation annuelle de 11,5 pouces (29,2 cm) et presque tout l'écoulement se produit dans la saison des orages d'été de juin à septembre. La variabilité des précipitations dans le temps et l'espace domine toute relation pluie-écoulement, spécialement dans les plus petits sous-bassins (grands de quelques milles carrés au maximum). Les obstructions à l'écoulement dans les chenaux éphémères normalement asséchés deviennent de plus en plus

* Contribution of the Southwest Watershed Research Center, Agricultural Research Service, Soil and Water Research Division, USDA, in cooperation with Arizona Agricultural Experiment Station, University of Arizona, Tucson, Arizona.

** Research Hydraulic Engineers, Southwest Watershed Research Center, Agricultural Research Service, USDA, SWC, 442 East Seventh St., Tucson, Arisona 85705.

importantes avec l'étendue croissante du bassin. Alors que l'écoulement sur place peut valoir 20 à 25% en moyenne des pluies d'été, l'écoulement du bassin 58 milles carrés (148 km²) n'atteint en moyenne que 4% de la pluie d'été. La corrélation entre la pluie donnée par la méthode Thiessen et l'écoulement pour des pluies individuelles décroît avec l'étendue des bassins du fait de l'étendue limitée des pluies d'orage et du fait aussi de l'accroissement des obstructions pour les grands bassins.

Les effets des pertes en transmission sur les écoulements des chenaux se traduisent par des modifications de l'hydrogramme en forme, hauteur et volume : elles ont été étudiées. Les hydrogrammes de sortie ont été prévus pour une section de 4 milles (6,4 km) de Walnut-Gulch, sans arrivée de tributaire, en utilisant une technique de régression et une distribution gamma à trois paramètres. Ce travail sera continué pour d'autres sections avec des conditions physiques différentes. A remarquer que les plus forts orages ont suivi des périodes relativement sèches quand le chauffage convectif de la surface du sol est possible du fait de la moindre nébulosité et des conditions plus sèches de surface.

## Introduction

The Southwest Watershed Research Center of the Agricultural Research Service operates the 58-square-mile (148 km²) Walnut Gulch Experimental Watershed in southeastern Arizona, U.S.A. (fig. 1). Two-thirds of the rangeland watershed is dominated by brush; one-third by grass. There is no cultivation. Most of the watershed is grazed by cattle, and a small part is urban (the town of Tombstone). The Walnut Gulch watershed is fairly representative of several hundred thousand square miles of semiarid rangeland in the Southwestern United States, as well as of other similar semiarid rangelands throughout the world.

Rain gages were first placed on the watershed in 1954, and at present precipi-

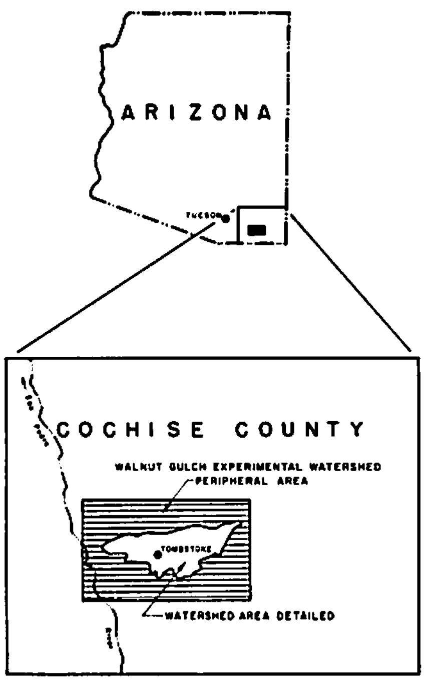


FIGURE 1. *Walnut Gulch Experimental Watershed location map.*

tation is measured with a network of 95 weighing-type recording rain gages (fig. 2). The principal watershed is subdivided into 20 subwatersheds. Surface runoff from these smaller units, as well as from the principal watershed, is determined with continuous water-level recorders at concrete control structures on the ephemeral channels. There are also several groups of plot studies, where the effects on onsite runoff of such variables as vegetation, soils, and surface conditions are studied more closely (Kincaid, Osborn, and Gardner, 1966; Schreiber and Kincaid, 1967).

## Watershed Characteristics

The Walnut Gulch watershed is butterfly shaped with the maximum length about 13 miles (21 km) and the maximum width about 5 miles (8 km). The watershed outlet lies at an elevation of just under 4000 feet (1200 meters) above mean sea level, while the upper reaches of the watershed rise to over 6000 feet (1800 meters). The watershed is drained by an extensive and well-defined channel system. Channels are clearly defined on even the smallest instrumented watershed (0.5 acre or 0.002 $km^2$). Onsite runoff moves relatively rapidly into well-defined channels.

The lower two-thirds of the watershed is dominated by native shrubs, while the upper end is primarily native grasses. The watershed is generally rolling with very little land suitable for cultivation. The major channels have about a one-percent slope. The channels are generaly filled with highly porous, relatively coarse-grained alluvial material. Infiltration rates at the beginning of flow often exceed 10 inches per hour (25.4 cm per hour) and decreases during the flow to about 1 to 2 inches per hour (2.54 to 5.08 cm per hour).

## Precipitation

In southeastern Arizona precipitation is seasonal. In the summer, the combination of moist air moving into the region from the Gulf of Mexico and strong convective heating produces thunderstorms. Most thunderstorms occur in the late afternoon or early evening and produce high-intensity, short-duration rains of limited areal extent. Winter storms, on the other hand, result from weak cold fronts and produce relatively low-intensity rainfall [generally less than 0.1 inch per hour (0.25 cm/hr)]. Occasionally in the late summer, a tropical storm off Baja California forces additional moist air into the region, which may increase thunderstorm potential.

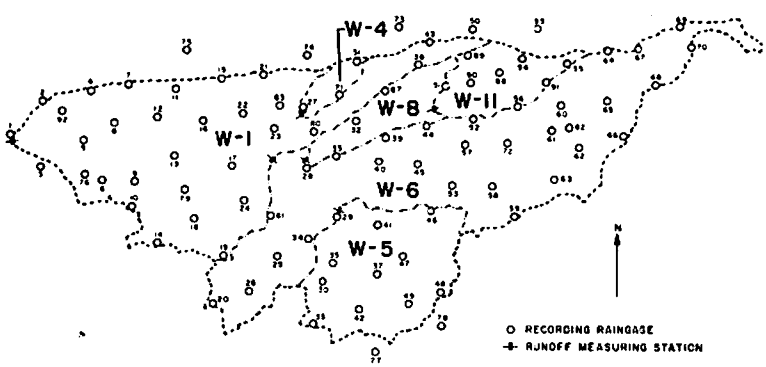


FIGURE 2. *Walnut Gulch Experimental Watershed*

On Walnut Gulch about 70 percent of the annual precipitation of 11.5 inches (29.2 cm) occurs from June through September (Osborn and Hickok, 1968). Summer rainfall is highly variable from year to year as well as over the watershed. Generally, the highest summer point rainfall is more than twice the lowest. For example, about 10.5 inches (26.7 cm) and 4.8 inches (11.9 cm) were the maximum and minimum recorded point rainfall depths for the summer of 1963. Storm rainfall varies much more, with some parts of the watersheds generally remaining dry while other parts are receiving runoff-producing rainfall. The extreme variability of thunderstorm rainfall is by far the major factor in determining rainfall-runoff relationships.

## Runoff

### *Onsite Runoff*

Because of the high intensities of rainfall, onsite runoff normally commences within minutes after the rain begins. Rainfall intensities can exceed infiltration rates by 10 to 1, and infiltration rates during the short-lived storms depend generally on the condition and type of soil in the top few surface inches. Runoff-producing rainfall (roughly, rain with intensities exceeding 0.5 inch per hour, or 1.27 cm per hour) seldom lasts for more than 30 minutes at any one point. In general, two-thirds of the total storm rainfall occurs in the first 20 minutes of the storm (Osborn and Reynolds, 1963). Onsite runoff may average as much as 20 to 25 percent of summer rainfall.

### *Channel Flow*

The ephemeral sand channels on the Walnut Gulch watershed are dry most of the year. Surface flows are limited generally to a relatively few afternoons and evenings during the summer. Approximately 10 to 15 runoff events might be expected annually

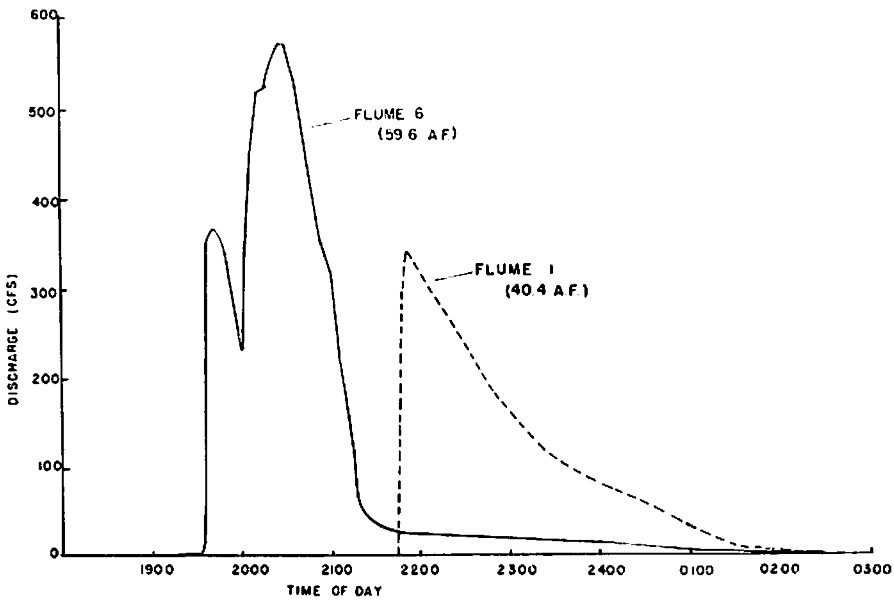


FIGURE 3. *Walnut Gulch Experimental Watershed hydrographs for August 2, 1964, Flumes 1 and 6*

on a 30-to 50-square-mile (74 to 127 km$^2$) watershed. Fewer events are recorded on the smaller watersheds. For the larger watersheds of 30 to 50 square miles (74 to 127 km$^2$), the duration of annual storm streamflow is about 2 to 3 days. In other words, the channels are dry over 99 percent of the time.

The average duration of flow for an individual storm event is relatively short on the very small watersheds—on the order of one hour. It is considerably longer on the larger watersheds—on the order of 6 hours. Variations in durations between similar sized watersheds are primarily due to differences of the alluvial channels, both in areal extent and in confining layers below the alluvium. Occasionally, local surface conditions such as urban development (Tombstone) or impervious rock

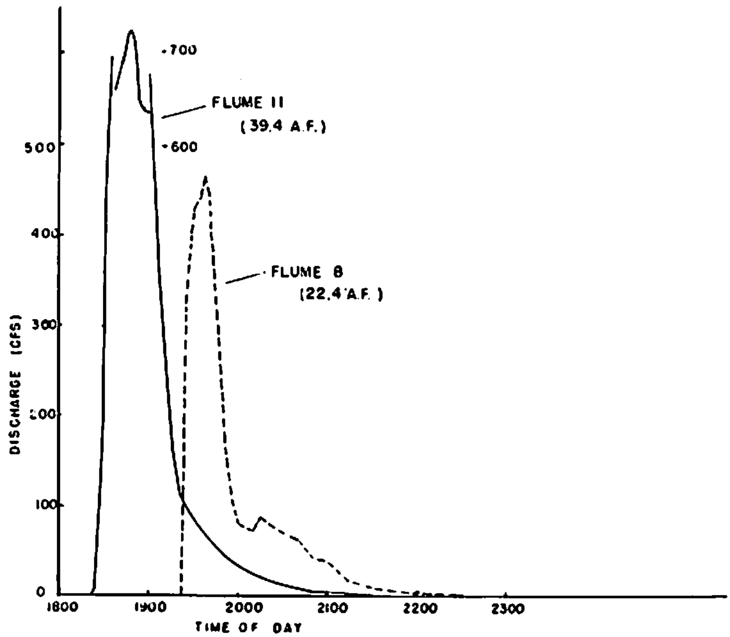


FIGURE 4. *Walnut Gulch Experimental Watershed hydrographs for August 2, 1964, Flumes 8 and 11*

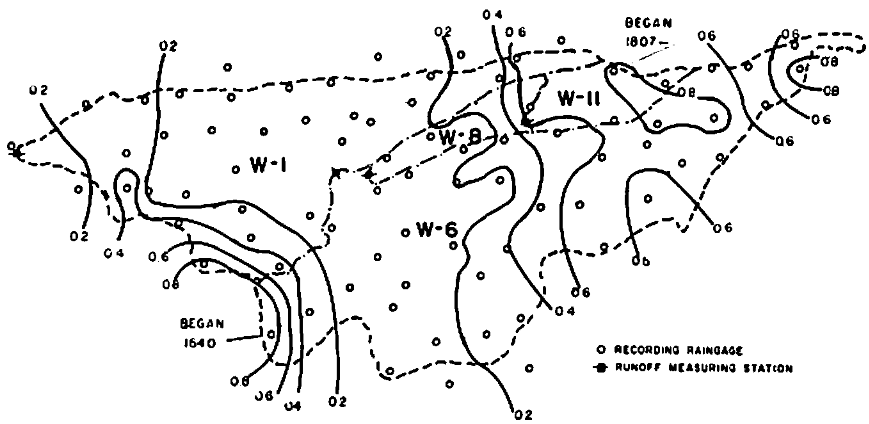


FIGURE 5. *Walnut Gulch Experimental Watershed rainfall on August 2, 1964*

barriers may influence the duration or number of events recorded at a particular station.

Because the streambeds are dry most of the year and because of the large volumes of alluvial material in the streambeds, runoff reductions are large as the water moves downstream. These flow reductions, or transmission losses, are extremely important in evaluating the hydrologic response of ephemeral streams in the Southwestern United States.

Transmission losses are measured on Walnut Gulch by comparing the inflow and outflow hydrographs for individual storms for channel reaches having little or no unmeasured tributary inflow. Because of the limited areal extent of the runoff-producing precipitation and the density of runoff-measuring sites, losses are evaluated from several storms in most years. The large critical-depth flumes measuring runoff from the larger complex watersheds [drainage areas >560 acres (220 hectares)] create seven channel segments with average bottom widths varying between 36 feet (12 meters) and 217 feet (71 meters) and channel lengths varying between 0.9 and 4.0 miles (1.4 and 6.4 km). Data show that the transmission losses are related to: (1) channel length and wetted perimeter; (2) hydrograph characteristics; (3) antecedent moisture conditions of the alluvium; (4) volume and porosity of the alluvium; (5) amount of clay in suspension in the water infiltrating into the alluvium.

Examples of transmission losses are shown in figures 3 and 4 for the storm of August 2, 1964. The rain on the lower portion of the watershed as shown on the isohyetal map (fig. 5) began at 1640 and produced only a trace of runoff at the watershed outlet (Flume 1) between 1900 and 2000 hours (fig. 3). The storm on the upper portion of the watershed began at 1807 hours and produced the runoff beginning at 1820 hours at Flume 11, as well as a significant amount of runoff in other tributaries above Flume 6. The additional drainage area between Flumes 11 and 8 probably produced very little flow. Thus, the 726-cfs (25.6 $m^3$/sec) peak discharge and 39.4 acre-feet (890 $m^3$) of runoff were reduced to the 463-cfs peak discharge and 22.4 acre-feet (505 $m^3$) of runoff in the 4 miles (6.4 km) of channel between the two flumes. The runoff was further reduced in the 0.9 mile (1.4 km) of channel between Flumes 8 and 6 to a peak discharge of 365 cfs (12.8 $m^3$/sec), as indicated by the first

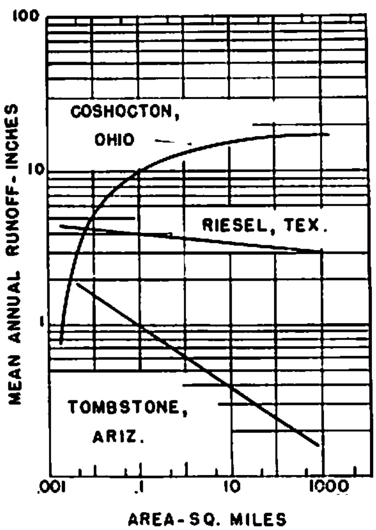


FIGURE 6. *Relationship between mean annual runoff and area*

peak on the recorded hydrograph. The double-peak hydrograph at Flume 6 resulted from runoff in the unmeasured tributaries above Flume 6 combining with the runoff from subwatershed 8.

The outflow hydrograph at Flume 1 demonstrates the effects of transmission losses and other channel hydraulic conditions on the hydrograph shape. The double-peak hydrograph at Flume 6 was changed to the triangular shape at Flume 1 as the flow traversed 6.8 miles (11 km) of relatively coarse-textured alluvium. The transmission losses, which are very large during early portions of the runoff, produce the truncation of the rising side of the hydrograph. Thus, for storm events traversing long reaches of stream channel, the rising limb of the hydrograph can be represented as a straight line, and the receding limb can be represented by an exponential decay (Renard and Keppel, 1966).

Figure 6 from a paper by Glymph and Holtan (1969) shows that the relationship between mean annual runoff and area changes for different physiographic and climatic provinces. In the semiarid Southwest, the streambeds absorb all of the runoff from many storms. There is little base flow. The transmission losses thus affect runoff per unit area, causing a decrease in runoff with increasing drainage area. In other areas such as Coshocton, Ohio, the runoff increases with increasing drainage area because of groundwater discharge.

Mathematical modeling of transmission losses has been limited. Recently, however, Lane, Diskin, and Renard (submitted for publication 1970) successfully predicted downstream hydrographs using regression techniques and a three-parameter gamma distribution to represent the inflow and outflow hydrographs for the 4-mile (6.4 km) reach of channel between Flumes 11 and 8. Using the known parameters of the inflow hydrograph at Flume 11 and two fitting methods, outflow hydrographs were obtained at Flume 8 for the storm of August 2, 1964 (fig. 7). The predicted volume of runoff at Flume 8 was 22.9 acre-feet (510 m$^3$), which agreed very well with the measured volume of 22.3 acre-feet (500 m$^3$).

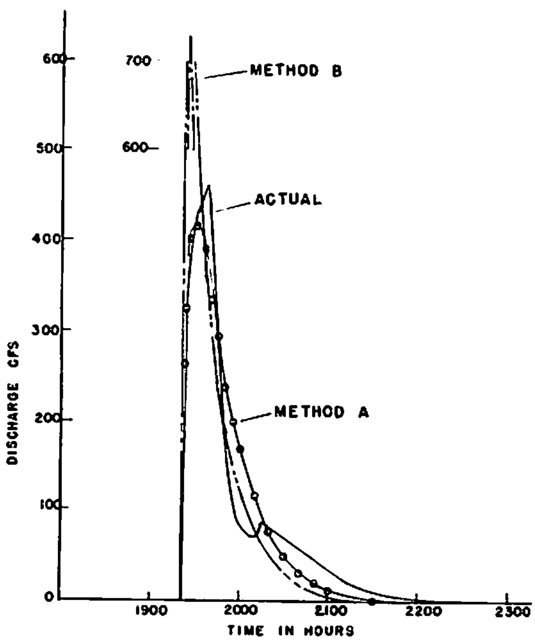


FIGURE 7. *Predicted and actual hydrographs for August 2, 1964, Flume 8*

Two methods were used to predict the gamma distribution parameters used to represent the outflow hydrograph from the properties of the inflow hydrograph. Method A involved the simultaneous solution of the equations for the mean and the mode of the gamma distribution to determine the parameters of the theoretical distribution. Method B involved the solution of the equations for the maximum ordinate and the interval between the mean and the mode to obtain the parameters of the theoretical distribution. In both methods, the third parameter of the theoretical distribution was equated to the time of start of the observed hydrograph.

In the illustration used, Method B overestimated the peak discharge, as well as displacing the peak toward the beginning of the storm (increased the skew). This was not true in all of the events used in the analysis, and the authors concluded that the two methods used to fit the gamma distribution to the outflow hydrographs were about equal in giving a good representation of the hydrograph.

Additional work is in progress using this procedure on additional channel segments of Walnut Gulch as well as on other ephemeral channels in the Southwestern United Stats. Hopefully this work will relate the coefficients of the regression equations with the physical characteristics of the streams to provide a regional description of transmission losses.

## Correlation of Rainfall and Runoff

For very small watersheds, runoff can be directly correlated to point rainfall values by simple regression equations (Osborn and Lane, 1969). About 70 to 80 percent of the variability in peak discharge and runoff volume was explained by the variability in either the maximum 15-minute or total rain depths for 4 very small watersheds [0.5 to 11 acres (0.2 to 4.5 hectares)]. In general, the variability of thunderstorm rainfall so dominated the rainfall-runoff relationships that no other single variable appreciably improved the initial regression equation.

$$Q = a + bP_{15}$$

and

$$V = c + dP_{tot}$$

where

$Q$ = peak discharge in inches per hour;
$V$ = volume of runoff in inches;
$P_{tot}$ = total storm rainfall in inches;
($a$ and $c$ are both negative values).

For larger watersheds (over one square mile) runoff was best correlated to the maximum 30-minute rainfall for both peak discharge and total storm runoff. Simple correlations between the maximum 15- and 30-minute point rainfall values and peak ($Q$) and total ($V$) discharge are shown in table 1. As would be expected, the best correlations were for the very small watersheds.

For watersheds less than 120 acres (49 hectares), point rainfall from a single gage gave good rainfall-runoff correlations. For the 560-acre (220 hectares) watershed, W-4, with a 3-gage network, the correlations were poor, and the differences between using the central gage and average rainfall were not significant.

Correlations between point rainfall values and runoff for 4 larger watersheds, W-11, W-5, W-6, and W-1 also are shown in table 1. For each of these stations, 20 to 26 events were chosen from the period 1961-68. These events represented all but one of the major recorded runoffs for which there was good record. One event, which produced significant runoff at 3 of the 4 stations, was deleted since it occurred

TABLE 1. Coefficient of Determination of Rainfall and Runoff for Eight Walnut Gulch Watersheds.

| Watershed | area | Runoff variable | Coefficient of determination($R^2$) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | *P15* | | | *P30* | | |
| | | | Ave. | Max. | Central | Ave. | Max. | Central |
| | (acres) | | | | | | | |
| LH-5 | 0.5 | *V/A* | | | 0.81* | | | 0.77* |
| | | *Q/A* | | | 0.85* | | | 0.74* |
| LH-3 | 8.5 | *V/A* | | | 0.85* | | | 0.85 |
| | | *Q/A* | | | 0.88* | | | 0.86* |
| K-1 | 120. | *V/A* | 0.61 | 0.60 | 0.60 | | | |
| | | *Q/A* | 0.72 | 0.72 | 0.71 | | | |
| W-4 | 560. | *V/A* | 0.48 | 0.37 | 0.41 | | | |
| | | *Q/A* | 0.48 | 0.37 | 0.43 | | | |
| W-11 | 2,030. | *V/A* | | | | 0.71 | 0.67 | ** |
| | | *Q/A* | | | | 0.76 | 0.66 | ** |
| W-5 | 5,500 | *V/A* | | | | 0.35 | 0.23 | 0.33 |
| | | *Q/A* | | | | 0.33 | 0.33 | 0.28 |
| W-6 | 23,500 | *V/A* | | | | 0.60 | 0.48 | 0.53 |
| | | *Q/A* | | | | 0.50 | 0.46 | 0.49 |
| W-1 | 36,900 | *V/A* | | | | 0.24 | 0.15 | 0.34 |
| | | *Q/A* | | | | 0.24 | 0.35 | 0.27 |

* Only one rain gage for the very small watersheds.
** No "central" gage on the W-11 watershed until 1966.

only 8 hours after another major event. All other events were separated by at least one day. In general, except for the occasional "double" event, antecedent rainfall and prestorm channel conditions account for less than 10 percent of the variability in runoff. Rainfall variability was by far the most significant variable for explaining runoff.

The results shown in table 1 probably are not conclusive, however. The records were relatively short and the range of runoff magnitude varied considerably between stations. For example, there were no "large" runoff events on W-4 between 1961 and 1968, whereas all other stations recorded a good range of storms from small to large. Also, there are three large stock ponds amounting to over 20 percent of the watershed area on W-5, which confounds the rainfall-runoff relationship there. Therefore, correlations for W-4 and W-5 would be expected to be considerably poorer than those for the other 6 watersheds, other factors remaining equal.

The correlations between rainfall and runoff for W-11, W-6, W-5, and W-1 could be rated as good, poor, poor, and nonexistent for the 4 watersheds, respectively. The most significant point here was the difference in correlation between W-6 and W-1. There was obvious correlation, although admittedly poor, between rainfall and runoff for W-6, and just as obvious a lack of correlation on W-1. The amount of difference would appear to rule out chance. Probably, the combined effect of the limited areal extent of the runoff-producing thunderstorm and the larger channel abstraction between Station W-6 and W-1 cause the difference.

Most major runoff events appear to cover from 25 to 35 square miles (65 to 91 $km^2$) with runoff-producing rainfall [over 0.5 inch (1.27 cm) in less than one hour]. Such events come much closer to covering the 37-square-mile (94 $km^2$) W-6 watershed than the 58-square-mile (147 km²) W-1 watershed; therefore, an average rainfall value on W-6 is meaningful, whereas on W-1 it is not.

There was no "key" gage from which rainfall and runoff would be significantly correlated on the W-1 watershed. Furthermore, there was no "best" gage for rainfall-runoff correlation on the W-5 and W-6 watersheds, and the data were not sufficient to prove or disprove the "key" gage theory on W-11.

The largest runoff events with the highest peak discharges all occurred after relatively dry periods. The record is too short to determine conclusively whether this is by chance or has real meaning. However, other records, plus some conclusions concerning the mechanics, or thermodynamics, of thunderstorms, strongly suggest that it is not chance. Surface temperatures are generally lower following a period of runoff both because of the evaporative cooling at the ground level and the greater likelihood of cloud cover. The chances for thunderstorms to occur in the summer under such conditions are excellent, but there seems to be little chance of an extreme storm developing.

This, then, would eliminate the concept of the maximum flood occurring from the maximum probable rainfall on a saturated watershed. Furthermore, the "maximum" rainfall appears to be so much larger than what can occur on a saturated watershed that it would produce a significantly greater peak discharge than the largest possible rainfall on a previously saturated watershed.

## REFERENCES

Kincaid, D.R., Osborn, H.B. and Gardner, J.L. (1966): Use of unit source watersheds for hydrologic investigations in the semiarid Southwest. *Water Resoursec Res.*, 2(3), 381-392.

Schreiber, H.A. and Kincaid, D.R. (1967): Regression models for predicting on-site runoff from short-duration convective storms, *Water Resources Res.*, 3(2), 389-395.

Osborn, H.B., and Hickok, R.B. (1968): Variability of rainfall affecting runoff from a semiarid rangeland watershed, *Water Resources Res.*, 4(1), 199-203.

Osborn, H.B. and Reynolds, W.N. (1963): Convective storm patterns in the Southwestern United States, *Internatl. Assoc. Sci. Hydrol. Bull.* 8(3), 71-83.

Renard, K.G. and Keppel, R.V. (1966): Hydrographs of ephemeral streams in the Southwest, *J. Hydraul. Div.*, ASCE 92 (HY-2), 33-52.

Glymph, L.M. and Holtan, H.N. (1969): Land treatment in agricultural watershed hydrology research. *In* Effects of watershed changes on streamflow, *Water Resources Symp. No. 2*, Univ. Texas Press, Austin, pp. 44-68.

Lane, L.J., Diskin, M.H. and Renard, K.G. (1970): Input-output relationships for an ephemeral stream channel system, *Submitted for publication in Water Resources Res.*

Osborn, H.B. and Lane, L.J. (1969): Precipitation-runoff relationships for very small semiarid rangeland watersheds, *Water Resources Res.*, 5(2), 419-425.

Ceuterick, Printers 153 Brusselse straat 3000-Louvain (Belgium)