Thunderstorm runoff in southeastern Arizona.

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THUNDERSTORM RUNOFF IN
SOUTHEASTERN ARIZONA

by

Herbert Bradley Osborn

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GRADUATE COLLEGE

I hereby recommend that this dissertation prepared under my direction by **Herbert Bradley Osborn**

entitled **"Thunderstorm Runoff in Southeastern Arizona"**

be accepted as fulfilling the dissertation requirement of the degree of **Doctor of Philosophy**

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SIGNED: Herbert Bradley Osborn

DEDICATION

to Lovinna

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ABSTRACT

Almost all runoff-producing rainfall on small watersheds (100 square miles and less) in southeastern Arizona results from air-mass thunderstorms. On large watersheds (1,000 square miles and greater) frontal systems which may include thunderstorm activity or snowmelt produce the major flood peaks as well as much of the annual runoff. Air-mass thunderstorms are of short duration and limited areal extent, and generally occur in the late afternoons and early evenings in July, August, and September. Runoff-producing rainfall may occur from frontal-convective systems at any time although they are most common in southeastern Arizona in September.

Rainfall and runoff records have been collected from the 58-square-mile Walnut Gulch rangeland watershed near Tombstone in southeastern Arizona by the Agricultural Research Service since 1954. These data represent the best information available on thunderstorm rainfall-runoff relationships in the Southwest. At present there are 95 recording rain gages and 22 permanent runoff-measuring stations on the Walnut Gulch watershed.

Runoff-producing thunderstorm rainfall is extremely variable both in time and space, and is therefore difficult to measure accurately and define precisely. Isohyetal mapping for rainfall from individual thunderstorms both for total rainfall and shorter durations within the storm provides good qualitative information, and also

provides some quantitative limits on storm movement, intensities and volumes, and areal extent.

Runoff records from Walnut Gulch and other Arizona watersheds indicate that peak discharge and runoff volume from individual thunderstorms decrease with increasing watershed size because of the limited areal extent of runoff-producing thunderstorms and because of the increasing channel abstractions with increasing watershed size. Channel abstractions greatly alter runoff hydrographs as flood surges move through the ephemeral channel system.

Five major runoff-producing thunderstorms on Walnut Gulch between 1957 and 1967 were used to develop a model for the maximum expected rainfall in southeastern Arizona. The model was based on maximum 30-minute point rainfalls within the average 60-minute runoff-producing thunderstorm.

Over 2.5 inches of rainfall has been recorded in 30 minutes on Walnut Gulch during 3 thunderstorms in 15 years of record (1955-1969). A thorough search of U.S. Weather Bureau and other records indicated that no storms of this combined intensity and magnitude have been recorded in Arizona. Therefore, for design purposes, the expected mean 30-minute rainfall for southeastern Arizona was estimated as 3 inches.

Regression analysis was used to estimate peak discharges for major runoff events on Walnut Gulch and to develop a rainfall-runoff model for Walnut Gulch. Peak discharges were correlated with the maximum 30-minute rainfall, which was considered the core of runoff-producing rainfall for major runoff events. Antecedent channel conditions and distance between watershed outlet and runoff-producing

rainfall had little effect on the correlation. The coefficients of determination for the regression equation correlating thunderstorm rainfall and peak runoff were 0.92 and 0.84 for watershed 5 (8 square miles) and watershed 1 (58 square miles), respectively.

With the model for maximum expected rainfall and the rainfall-runoff model for estimating peak discharge from maximum 30-minute rainfall, maximum discharge for the 58-square-mile Walnut Gulch watershed was 23,000 c.f.s. Assuming a normal distribution of errors, within 95 percent confidence limits, the limits were 19,000 and 27,000 c.f.s., and assuming the Chebyshev inequality, the limits were 15,000 and 31,000 c.f.s.

Recurrence intervals for 20-, 50-, and 100-year storms and the maximum peak discharges were developed for small watersheds (100 square miles and less) from Walnut Gulch data. The curves were compared to a family of curves for Arizona watersheds up to several hundred thousand square miles. The family of curves based on Walnut Gulch data were much steeper, strongly suggesting that there are 2 families of curves, one steeper family for the small watersheds (100 square miles and less) which is based on runoff peaks from air-mass thunderstorms, and another flatter family of curves for the large watersheds (1,000 square miles and greater) which is based on runoff peaks from frontal-convective systems and snowmelt. The 2 families of curves probably intersect between 100 and 1,000 square miles.

CHAPTER 1

INTRODUCTION

The magnitude, frequency, duration, and time of occurrence of rainfall on small watersheds and the runoff consequent to this rainfall are of interest to many. In particular, the magnitudes of the flood peaks that may be expected with varying probability is often the characteristic of concern to the designer. For small watersheds, especially in the Southwest, the runoff-producing rain giving rise to "floods" is the thunderstorm.

Petterssen (1956) made the following distinction between thunderstorm types.

> Outside the intertropical belt, thunderstorms are observed to occur in three easily recognized patterns. (1) When an air mass is convectively unstable, sufficiently warm and moist, thunderstorms will be released in the upglide motion associated with frontal zones. Although the storms may be widely scattered, the general pattern moves along with the fronts with which they are associated. They are usually referred to as frontal thunderstorms. (2) Within more or less uniform air masses one finds an irregular pattern of individual storms, or clusters of such storms. These, which are usually referred to as air-mass thunderstorms, show a pronounced diurnal variation with a maximum in the afternoon and early evening. (3) Analyses of radar scopes show that thunderstorms not associated with fronts often have a tendency to be arranged in lines or bands more or less along the direction of the wind at low levels. These are called line thunderstorms. In strong cases the storms develop along distinct sheer lines, or squall lines, in the low-level wind field (p. 157).

In southeastern Arizona, almost all intense rainfall results from summer air-mass thunderstorms; in other regions in the Southwest, frontal-convective thunderstorms occur more often.

A paper by Luna B. Leopold (1944), and the spirited discussions by several persons which were published along with his paper, provide the earliest comprehensive information on thunderstorm rainfall in the Southwest. Leopold compiled available precipitation data from scattered rain gages throughout Arizona and New Mexico and calculated volumes for the maximum expected 24-hour storms for intervals of 5 to 100 years for scattered stations in the Southwest. For example, the 24-hour, 100-year rain for Tucson was estimated to be 3.60 inches. He also discussed the topographical and meteorological features that he felt influenced precipitation in the Southwest. He admitted, and others agreed, that his task was made difficult by the lack of long records and the scarcity of rain gages. These two problems still exist in most parts of the Southwest.

Since Leopold's paper, several persons have studied and published information on thunderstorm rainfall in the Southwest. Among these were McDonald (1957b), Woolhiser and Schwalen (1959), Sellers (1960), Workman (1962), Fogel (1968), and Fogel and Duckstein (1969). Also, several papers which were based on thunderstorm rainfall on the Walnut Gulch Experimental Watershed have been published. Osborn and Reynolds (1963) discussed the extreme variability of thunderstorn rainfall in general in the Southwestern United States; Osborn (1964) studied the effect of rainfall duration on runoff; Kincaid, Osborn, and Gardner (1966) described the extreme variability of thunderstorm rainfall on even very small watersheds (one square mile and less); Schreiber and Kincaid (1967) reported that rainfall completely dominated rainfall-runoff relationships for 72-square-foot rangeland plots; and Osborn and Lane (1969) found rainfall dominated rainfall-runoff relationships for very small semiarid rangeland watersheds (10 acres or less), as well.

Woolhiser and Schwalen (1959) used three years of rainfall records from the Atterbury watershed near Tucson, Arizona to develop a model for thunderstorm rainfall. In their model, rainfall depths decreased rapidly with distance from the center, and areal extent increased proportionally with increasing center depth.

"Arizona Climate," edited by Sellers (1960), includes excellent qualitative descriptions of thunderstorms and thunderstorm rainfall in Arizona. Sellers pointed out that there were, in effect, two overlapping thunderstorm seasons, one in July and August when moisture moves into Arizona from the Gulf of Mexico, and one in September, when moist air may be pushed into Arizona by tropical storms in the Pacific.

Fogel (1968) pointed out that Wisler and Brater (1959) and Chow (1964) have included chapters on arid land hydrology in their books, but that these chapters provided only general information. Fogel further reported that Linsley (1953) and Wisler and Brater (1959) recognized that the fundamental difference between the hydrology of the arid and semiarid Southwest and the humid East was the extreme variability of precipitation both in time and space that is encountered in the predominantly semiarid Southwest.

Relatively little information is available on thunderstorm runoff in the Southwest. Fogel (1968) stated that "small watersheds, those under 100 square miles in area, are probably subjected to greater variations in response to precipitation than are the larger watersheds." The best source of data on thunderstorm runoff from small watersheds in the Southwest is probably the 58-square-mile Walnut Gulch Experimental Watershed in southeastern Arizona where rainfall and runoff records have been collected since 1954.

In this paper, models are developed through use of Walnut Gulch data and multiple linear regression to predict peak discharges from air-mass thunderstorm rainfall for small (100 square miles and less) semiarid rangeland watersheds in southeastern Arizona. Possible limits on the maximum intensity, duration, and areal extent of runoff-producing thunderstorm rainfall for this region are investigated. Maximum expected peak discharges are predicted for small watersheds from maximum expected runoff-producing rainfall and the rainfall-runoff models. The uncertainty in recurrence intervals for "record" peak discharges due to relatively short periods of record, and the sensitivity of maximum predictions because of possible errors in sampling or inadequacies in the rainfall-runoff equation are investigated. Possible applicability of results to other watersheds and regions is discussed.

Mechanics of a Thunderstorm

Haltiner and Martin (1957) gave a brief summary of the "life" of a thunderstorm based on the results of a thunderstorm research project by the U.S. Weather Bureau (1949). The structure of an air-mass thunderstorm was described as being composed of 3 to 7 cells, not necessarily concurrent in development, with each cell going through a life cycle of 3 stages--cumulus, mature, and dissipating--and with the entire thunderstorm lasting on the order of 3 hours.

In the cumulus stage there is an updraft that is warmer than the environment and extends through the developing cumulus cloud. Gentle winds converge over the surface toward the slightly lower pressures below the updraft. There is no precipitation in the cumulus stage.

The updraft continues, and the size of the water droplets and ice crystals increase until some can no longer be supported by the updraft. The falling droplets enlarge, primarily by collision with smaller droplets, and tend to drag air downward, causing a downdraft adjacent to the updraft within each cell. The transition from cumulus to mature stage may be identified with the first rain reaching the ground surface. Very high rain intensities may be observed in the mature stage. As the rain continues, the downdraft spreads both vertically and horizontally from the lower central portion of the cell. Cool air moves out from the downdraft at the ground surface and eventually cuts off the supply of warm air to the updraft. Temperatures drop, and gusty winds are observed at the surface. When the updraft is cut off, the mature stage has ended. The mature stage normally lasts approximately 15 to 30 minutes, but may last for almost an hour.

The dissipating stage lasts approximately 20 minutes. The spreading downdraft virtually eliminates upward movement, and precipitation decreases to very low intensities or ceases altogether.

Workman (1962) pointed out from his observations in western New Mexico that a runoff-producing thunderstorm "requires a vast amount of space from which to derive its water and energy" (p. 409). He further stated that although it was difficult to analyze thunderstorms quantitatively, a good estimate would be that "a convective thunderstorm typical of the Southwestern United States requires a region of atmosphere covering 1,000 or more square miles of land to develop and sustain its action" (p. 409). Workman did not estimate the time involved in development of a thunderstorm, but did imply that only one major thunderstorm could occur within the region of "1,000 square miles" in one afternoon.

Current Practices in Engineering Design

Designers today use several methods to determine flood peaks and frequencies. Linsley, Kohler, and Paulhus (1958) reported that "the most widely used design equation for small basins is given the misleading name of 'rational formula,'

$$q_p = CiA \qquad (1.1)$$

where q_p is in acre-inches per hour, i is average rainfall intensity in inches per hour for a duration equal to the time of concentration of the basin, and A is area in acres" (p. 212). In the rational formula, C is runoff coefficient based on watershed characteristics.

The Soil Conservation Service has developed two methods for estimating volume and rate of runoff--one for watersheds of about 2,000 acres and less, and one for watersheds of more than 2,000 acres. Kent (1968) states that one S.C.S. method is limited to small watersheds, while the second is used "primarily for planning and designing measures--larger than those for farm and ranches--in watersheds planned under the Watershed Protection and Flood Prevention Act" (p. 1).

A widely used method for flood-frequency analyses has been developed over many years by the United States Geological Survey. The method applies generally to larger watersheds than those investigated by the S.C.S. and is limited to determining expected peak discharges for given recurrence intervals.

Linsley, Kohler, and Paulhus (1958) pointed out that the rational formula has the advantage of simplicity and its physical meaning is reasonably clear, but that it may involve serious errors for watersheds over a few acres in size. The rational formula is rational if the watershed is small enough so that the rain is uniform over the entire area and lasts long enough so the runoff is equal to the rainfall excess. Since these very restrictive conditions are seldom met, judgement in choosing the "C" value must consider many, many factors--few of which are simple and straightforward. Studies based on data from the Walnut Gulch Experimental Watershed in southeastern Arizona suggest that since runoff-producing thunderstorm rainfall in the Southwest tends to be dominant over watershed characteristics for very small watersheds, the Rational Formula may be applicable for watersheds of about 100 acres or less, but probably not for ones very much larger.

The two S.C.S. methods are probably the most sophisticated of those that are widely used. These methods are based on rainfall amount, hydrologic soil-cover complexes, and antecedent moisture conditions. The hydrologic soil complex consists of four major soil groups which are grouped as to infiltration and soil-water movement. The four groups, listed A (the lowest runoff potential) through D (the highest runoff potential) contain every soil series found in the United States. The cover complex is determined by land use and treatment classes. The land use and treatment of an area is further divided into 3 hydrologic conditions--poor, fair, or good. Antecedent moisture condition is based on the summation of 5-day antecedent rainfall. Knowing the watershed conditions and characteristics, one can determine the appropriate runoff curve number from the S.C.S. Hydrology Handbook. Kent (1968) admitted large differences in peak rates determined under similar conditions, but attributed these differences to choices of coefficients in the methods. However, at least for the Southwest, differences may be largely because of rainfall variability and channel abstractions, rather than from differences in watershed characteristics.

A graphical method of flood frequency analysis developed by the U.S.G.S. for use on the Colorado River Basin was outlined by Patterson and Somers (1966) in Water Supply Paper 1683. The paper includes description of flood frequency regions and hydrologic areas within the Basin. The regions and areas were determined by plotting the mean annual flood as determined from data at gaged stations and grouping stations that plotted together. Peak discharges for desired recurrence intervals are then directly determined from two sets of curves in Water Supply Paper 1683. The first set of curves gives the mean annual flood versus watershed area for certain bounded hydrologic regions; and the second set of curves gives the ratio of peak discharge at different recurrence intervals to the mean annual flood. Patterson and Somers wrote that "the range of these curves is limited by the data upon which the curves are based; extrapolation of the curves beyond indicated basin size, basin altitude, and recurrence intervals exceeding 50 years is not dependable" (p. 27). They also stated that "extrapolation of curves to small areas at low altitudes could lead to serious error." However, the method is widely used by engineers faced with design decisions and very little data of their own. Also, by necessity, the method is extrapolated to recurrence intervals of greater than 50 years. For watersheds of less than 100 square miles, engineers generally use other methods, including the Rational and S.C.S. methods.

CHAPTER 2

RELATED STUDIES

This section deals with some pertinent studies in related areas of hydrologic research. This literature review falls roughly into four categories--rainfall, rainfall-runoff relationships, extreme rainfall and runoff values, and the question of uncertainty and error in peak discharge predictions.

Rainfall

Bell (1969) restated a well-known but sometimes overlooked fact that "the magnitude of a rainfall event is given by the total depth occurring in a particular duration. In some past analyses the mean intensity has been used instead of the total depth but this has sometimes given the misleading impression that rainfall intensities are approximately constant throughout the specified duration. In reality the intensity is highly variable and rarely remains constant for more than a few minutes." Bell went on to point out that "the rainfall associated with the extreme floods of large streams is of relatively long duration while the rainfall associated with the floods of smaller streams is of shorter duration" (p. 311).

Leopold (1942) described several exceptional rains in Arizona and New Mexico. Isohyetal maps of total rainfall were based primarily on 24-hour records, with estimates of duration. He reported a 2-hour rainfall of 5 inches in the White Mountains of Arizona and about 7 inches of rainfall in 4 hours in Las Cruces, New Mexico.

Woolhiser and Schwalen (1959) and Fogel and Duckstein (1969) developed models for thunderstorm rainfall from records from the Atterbury watershed near Tucson, Arizona. In these models areal extent was taken as directly proportional to center depth. There are 26 standard and 6 recording rain gages on the 20-square-mile rangeland Atterbury watershed. The Atterbury and Walnut Gulch watersheds are the only two densely instrumented experimental watersheds in southern Arizona.

Fogel and Duckstein (1969) assumed that 24-hour rainfall amounts in southern Arizona in July, August, and September usually resulted from short-duration, high-intensity thunderstorm rainfall. They did not determine a duration for individual thunderstorms, however, since they did not have enough recording rain gages to do so.

Rainfall-Runoff Relationships

Chow (1962) compiled, classified, and commented on equations used in design of drainage structures in small drainage basins. Among the close to 100 formulas were 24 based on rainfall intensity similar to the Rational method. Most of the 24 were developed for small urban or agricultural watersheds, but none were developed specifically for aird and semiarid watersheds.

Reich and Hiemstra (1965) estimated maximum flood peaks for watersheds from 1/5 to 5 square miles from 12 localities in the United States, based on the maximum 30-minute point rainfall, estimates of infiltration, and the time of concentration. One of the localities was in southeastern Arizona. Reich assumed runoff-producing rainfall covered the entire watershed. He also assumed that design storms for very small watersheds must result from summer thunderstorm rainfall. Although this might not be true for all regions, Reich felt that it was true for many parts of the world, and that his results applied to regions outside as well as inside the United States. Reich blamed the considerable scatter in his results primarily on difficulties in classifying or identifying soil types. He admitted that rainfall variability also was a problem in correlating rainfall and runoff.

Rainfall Extremes

Rainfall extremes and predicted maximum rainfall for many regions have appeared in various U.S. Weather Bureau technical papers in the past 10 years. U.S. Weather Bureau Technical Paper 38 (1960) gave generalized estimates of probable maximum precipitation for the United States west of the 105th meridian. The maximum recorded 1- and 24-hour rainfalls for southeastern Arizona up to that date were 2.4 and 6.1 inches, respectively. The theoretical probable maximum precipitation for one hour for southern Arizona was given as 12 inches. This estimate resulted primarily from transposing a "record" frontal-convective storm at Campo, California, which is in the mountains about 25 miles east of San Diego, across southern Arizona.

The following statement was also included in U.S. Weather Bureau Technical Paper 38 (1960): "While there is a tendency for persistence in weather, major storms are rare events that, in a sense, may be regarded as exceptions to persistence. Therefore, while it is physically possible for outstanding storms to repeat at intervals of something like 4 to 5 days, there is relatively little probability of the occurrence of such a series" (p. 52).

Hershfield (1961a) in U.S. Weather Bureau Technical Paper 40 determined depth-frequency curves for the United States. For southeastern Arizona, the 30-minute, 100-year rainfall ranged from 1.75 to 2.5 inches. Miller and Frederick (1966) in U.S. Weather Bureau Technical Paper 59 estimated the chance of occurrence of 24-hour rainfall exceeding 1, 2, and 4 inches. For southeastern Arizona for each of the summer months, July, August, and September, they estimated less than 0.01 chance of exceeding 4 inches of rainfall in 24 hours. No estimates were available for shorter durations.

Hershfield (1961b) also estimated probable maximum precipitation values for the United States. He used an entirely statistical approach from which he concluded that the probable maximum precipitation was within 15 standard deviations of the mean. (This is the same as saying that chances are roughly one in 50 billion that the rainfall will exceed that determined by this method.) In his study, the maximum recorded 24-hour rainfall for a long-term station in Arizona was 4.1 inches at Yuma.

In an extension of his earlier work, Hershfield (1962) arrived at several conclusions concerning maximum rainfall:

> Several hypothetical examples indicate that the magnitude of a rainfall equal to the mean plus 15 standard deviations is equivalent to a rainfall that is approximately three times the maximum observed from a long period of record. The mean of a series of annual maximum rainfalls multiplied by seven will envelop the maximum rainfall at the corresponding station. The

> maximum observed rainfall multiplied by a factor of 3.3 will provide an estimate of the maximum rainfall that is likely to occur at a station that might be too large but certainly not too small (p. 92).

According to Hershfield, therefore, maximum probable 24-hour rainfall at Yuma, for example, would be about 13 inches, as opposed to 12 inches in one hour as suggested in U.S. Weather Bureau Technical Paper 38. Hershfield felt that he did not have sufficient data to predict probable maximums for shorter durations of rainfall.

A few years later, Yevjevich (1968) revived the controversy over the concept of maximum probable precipitation. He stated that "persistent use of the concept of maximum precipitation and maximum probable precipitation for which there is no physical proof, has discouraged research into the structure and probability of extreme events, and may have led to an unwarranted sense of security concerning flood-control works" (p. 225).

Wilson (1968) in a discussion of Yevjevich's paper felt that Yevjevich had overstated his case. Wilson pointed out that people tend to concentrate in flood plains whether flood-control structures are built or not, and that rather than discourage research, the use of probable maximum precipitation has probably encouraged research on rainfall and rainfall mechanisms. More important, however, was the analysis of the problem as stated by Wilson (p. 1145):

> The problem of estimating beyond the range of observed data, by any method, involves many uncertainties. Advocates of the deterministic approach are not unanimous in their philosophy, terminology, or even methodology. Advocates of the stochastic approach do not necessarily agree on choice of distribution, how to handle wide confidence limits, or where to cut the tail of the distribution. The word 'probable' in 'probable maximum precipitation' is deliberate. It should remind users of the uncertainties in such estimates and should dispel any notions of zero risk.

Wilson also discussed probabilities of occurrence of rare events.

> It is believed that no one has succeeded in assigning meaningful probabilities to transposed rare events. This possibility should perhaps be investigated, but, in the meantime, it seems reasonable to examine the record of storms and other information with which to decide that this storm could happen here while there is no evidence that a much larger storm can occur (p. 1145).

Maximum Expected Peak Discharge

Linsley, Kohler, and Paulhus (1958) stated that design of major structures is often based on hydrometeorological studies because frequency analyses of streamflow data which are generally relatively short may not be satisfactory. The extrapolation of the known record depends both on the correctness of the chosen distribution and the accuracy of the measurements. Furthermore, the extrapolation will not indicate whether the flood magnitudes estimated in this fashion are meteorologically or hydrologically possible.

Ogrosky (1964) discussed the minimum spillway design used by the S.C.S. "Because nearly all sites for small dams are located in watersheds for which there are little or no hydrologic data available, the minimum (allowable) spillway design criteria are based on rainfall data analyses performed by the U.S. Weather Bureau (p. 295).

There have been several publications in the past ten years that have dealt either wholly or partially with the occurrence of extreme peak discharges in Arizona. Grove (1962) reported a survey of flood peaks from Arizona drainages going back to the 1880's. A portion of one figure from this report with Walnut Gulch peaks added is shown in Fig. 2.1. Lewis (1963) reported on the floods in late September 1962

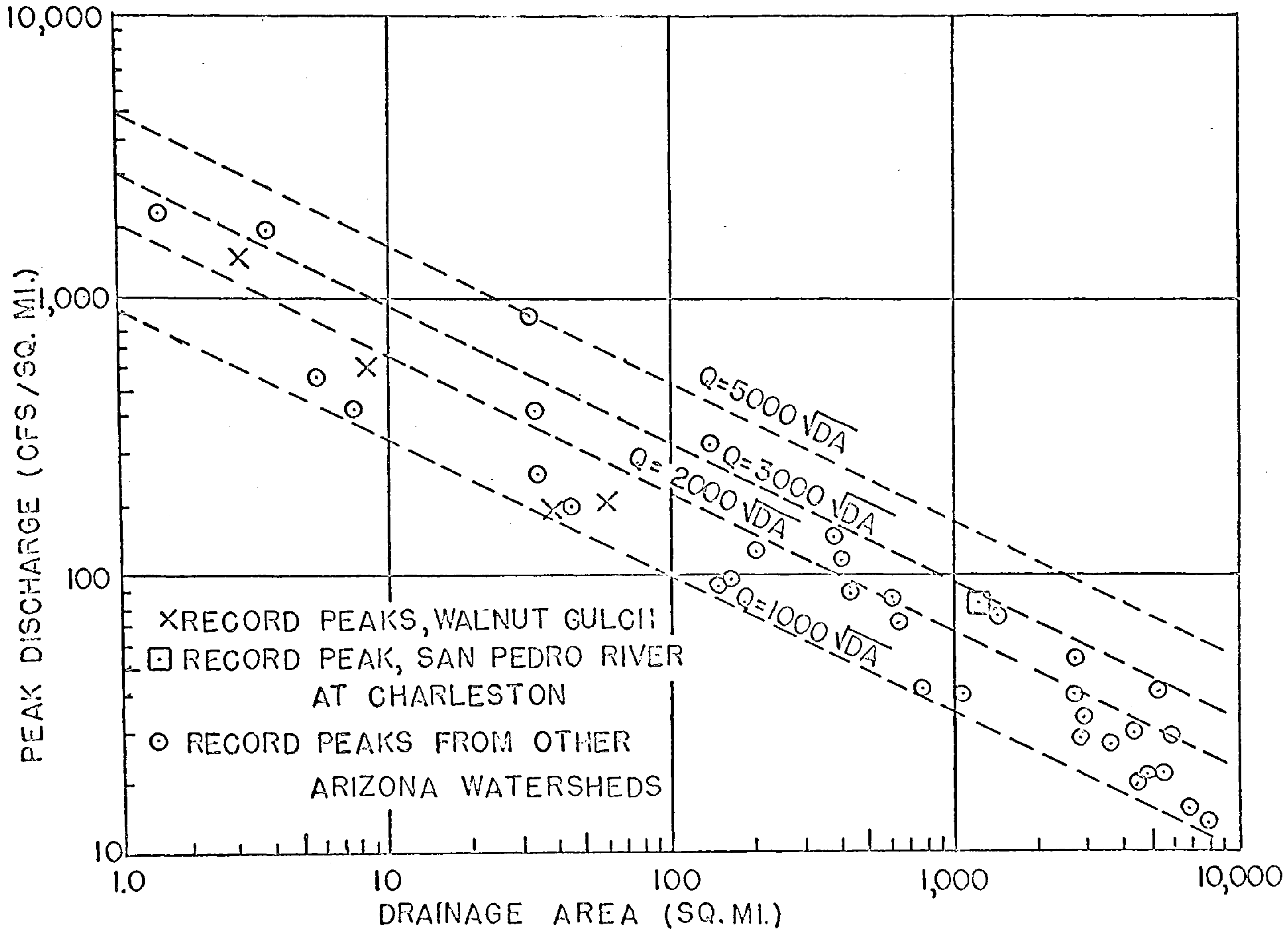

Fig. 2.1. Maximum flood peaks of record versus drainage area for Arizona watersheds, from a report by Grove to the joint Tucson-Pima County planning department, 1962

in southern Arizona. This storm produced the greatest measured peak discharges in the Santa Cruz Basin. Some of the maximum recorded and estimated peak discharges from watersheds south and west of Tucson during the 1962 storm are shown in Table 1.1.

Table 1.1. Maximum peak discharges for selected drainages for a major storm near Tucson, 1962

Drainage Area (sq. mi.)	Peak Discharge (c.f.s.)
5.3	2,700
4.0	4,000
11.9	13,800
1,080.0	38,800
1,780.0	53,100

Lewis also plotted the peaks on the same figure used by Grove a year earlier (Fig. 2.2). He stated, however, that "it must be emphasized that this illustration is not intended to define the maximum flood that may occur in the desert lowlands of Arizona, but is offered as a graphic representation of floods for which records are available."

As stated in Chapter 1, Patterson and Somers (1966) outlined methods by which the magnitude and frequency of expected floods from 1.1 to 50 years could be determined for most of the Colorado River Basin. They were unable to determine frequencies for most of south-central and southwestern Arizona, but they did establish flood frequencies for southeastern Arizona.

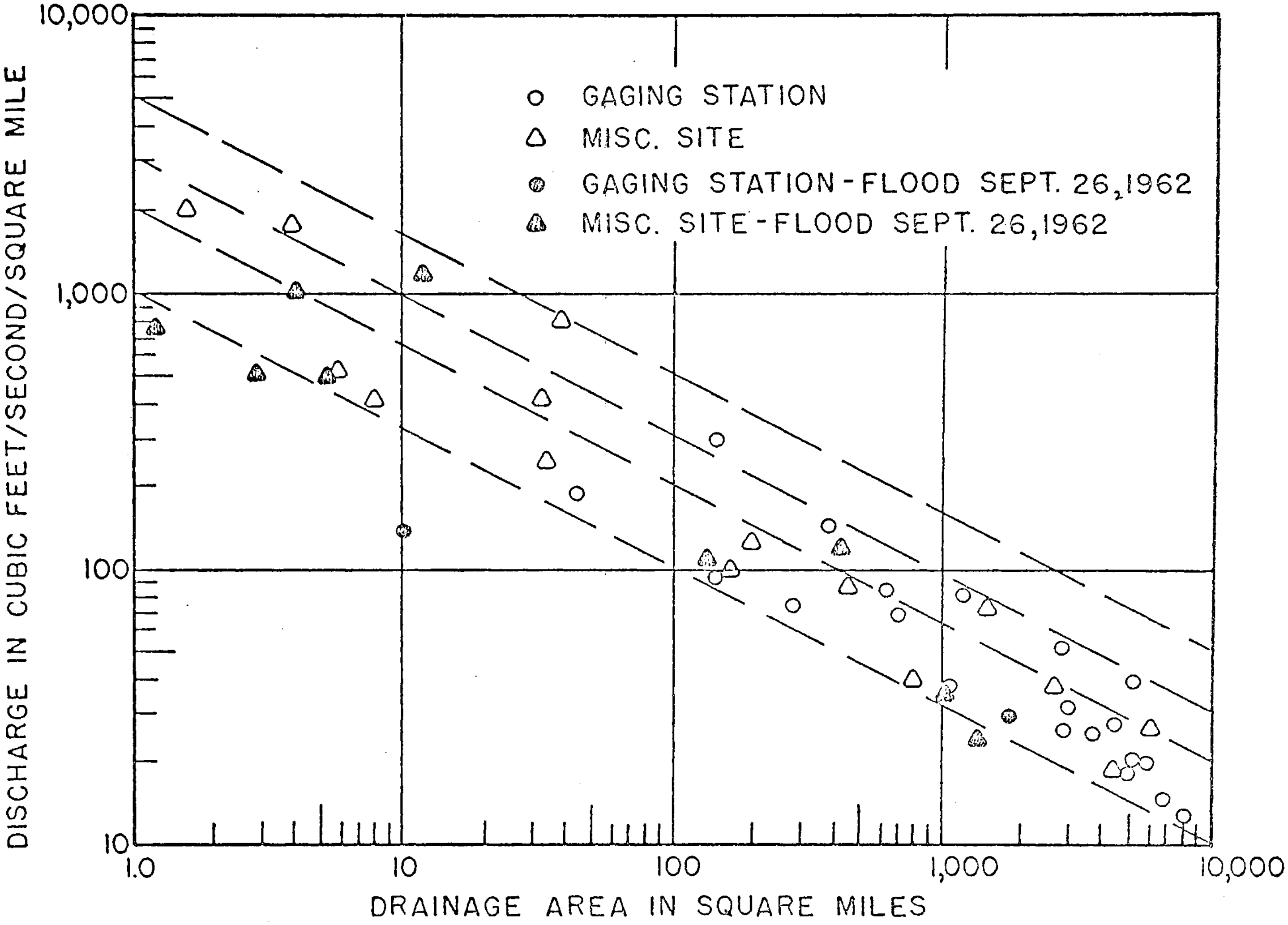

Fig. 2.2. Maximum flood peaks of record versus drainage area for Arizona watersheds (Sept. 1962 storm included), from Water Resources Report 13 by D. D. Lewis, Arizona State Land Dept., 1963

Alexander, Karoly, and Susto (1969) showed that there was a tendency for extreme-value probability distributions used to predict extreme floods to converge in their long tails. They stated that "once it is recognized that rare floods can be analyzed using statistical procedures, given sufficient incentive, we should ultimately be able to dispense with subjective methods such as the estimation of floods using the so-called 'probable maximum precipitation'" (p. 354). There are no known illustrations of actual data analyzed by their method. At present, they report that they are analyzing precipitation and floods given by Dalrymple (1965) with their model, but no report on this analysis is as yet available.

The hydrology committee of the Water Resources Council (1967) recommended the Log Pearson Type III method as the standard technique for determining flood flow frequencies. However, the hydrology committee agreed that "the state of the art with respect to flood flow techniques, as with most other hydrologic techniques, has not advanced to the point where complete standardization is feasible or appropriate" (p. 6). For that reason, the Committee recommended that "a base method be adopted with provisions for using other methods where adequate justification is presented" (p. 6). The Committee chose the Pearson Type III method as their "base" method, but did not state that it was the best method available. Benson (1968) summarized the report of the Hydrology Committee, but also allowed for "provision for departures from the base method where justified" (p. 904).

Sangal and Biswas (1970) discussed the advantage of using a 3-parameter lognormal distribution on frequency analyses of floods, annual flows, and monthly flows. They compared flood magnitudes for 10 Canadian rivers by 5 distributions, including the 3-parameter log-normal distribution for 5-, 10-, 50-, 100-, 1,000-, and 10,000-year recurrence intervals. The ratio of high to low predicted magnitudes of the 1,000-year flood flow ranged from 1.2 to 1.5. For the 10,000-year flood flow the ratio ranges from 1.2 to 1.8, with most ratios over 1.5.

Uncertainty and Error

Alexander, Karoly, and Susto (1969) quoted Moran (1957):

> In the first place the form of the distribution of floods is not known and any distribution used must be guessed. This may have a considerable effect since the part of the distribution we are interested in is well away from the part where the observations provide some information about the shape. It is therefore easy to construct two different distributions--both of which fit the observation closely but for which the tails are of quite different shape. This difficulty cannot be really surmounted, but we can try to fit several distributions and see how the choice affects the results. It would also be desirable to use some measure of goodness of fit on the fitted distribution (p. 325).

Benson (1964) used statistical multiple-regression techniques to investigate factors affecting flood occurrences in the Southwest; however, Arizona was not included in this report. The standard error for the predictions ranged from 43 to 62 percent. In his conclusions, Benson stated that "we would like to believe that we can predict floods of given recurrence intervals within closer limits than are represented in the standards that have resulted from this study. However, our present state of knowledge and conditions within this area now preclude any appreciable improvement for a long time to come" (p. 65).

Nash and Amorocho (1966) found that the standard error of estimate due to sampling variance for the magnitude of an assumed normal and double exponential distribution of floods far in excess of records available was not as great as might have been expected. However, the value of this study to others depends on choosing the correct distribution, and this is generally now known. They admitted that "the problem of error due to failure of the universe to conform to an assumed distribution is not treated" (p. 191).

Bell (1969) made several observations on the accuracy of recurrence intervals for floods of given magnitude. For example, he pointed out that within a 65-percent confidence interval, with 25 years of good record, the actual recurrence interval for the estimated 100-year event lies between 25 and 400 years.

Yen (1970) reported on the risks in hydrologic design of engineering projects:

> In the hydrologic design of engineering projects there are other risks and uncertainties involved in addition to the basic simple calculated risk previously mentioned. These risks and uncertainties arising from transformation of rainfall data to runoff information, from using a point record to represent an area, from considering the hydrologic system as a quasideterministic system or a stochastic system, and from the uncertainty of the mathematical techniques in handling the data and measurement errors. The hydrologic data of a limited period may not and usually do not represent exactly the true case of the complete population which usually consists of an infinite number of data over an infinite period (p. 963).

The quoted material from Yen (1970) is a good qualitative summary of the errors that may be hidden in any estimate of peak discharge for a desired recurrence interval. However, such estimates must be made in every-day engineering practice. Such estimates should be accompanied by both an estimate of possible error and some comparison with other popular methods.

CHAPTER 3

DESCRIPTION OF EXPERIMENTAL WATERSHED

Walnut Gulch is an ephemeral stream located in the San Pedro River drainage in southeastern Arizona. Southeastern Arizona is herein defined as the area bounded by Mexico on the south, the Huachuca, Whetstone, Rincon, and Catalina Mountains on the west, the Gila River on the north, and New Mexico on the east. If Arizona were divided into nine approximately equal sections, the southeastern section would cover approximately the area defined above. The Southwest Watershed Research Center of the Agricultural Research Service established a runoff-measuring station in 1954 on Walnut Gulch about two miles from the confluence of Walnut Gulch and the San Pedro River (Fig. 3.1). In this paper, the drainage area above this station, the Walnut Gulch Experimental Watershed, is referred to as the Walnut Gulch watershed, or simply Walnut Gulch.

The 58-square-mile Walnut Gulch watershed is representative of much of the brush-grass rangeland in southeastern Arizona and southwestern New Mexico. The lower two-thirds of the watershed is largely brush covered. Almost all of the watershed is grazed year round. Most of the watershed consists of gently rolling low hills. There are a few steeper hills on the southern boundary of the watershed below the small city of Tombstone, and also in the headwaters of the watershed in the Little Dragoon Mountains. The watershed ranges in elevation from 4,000

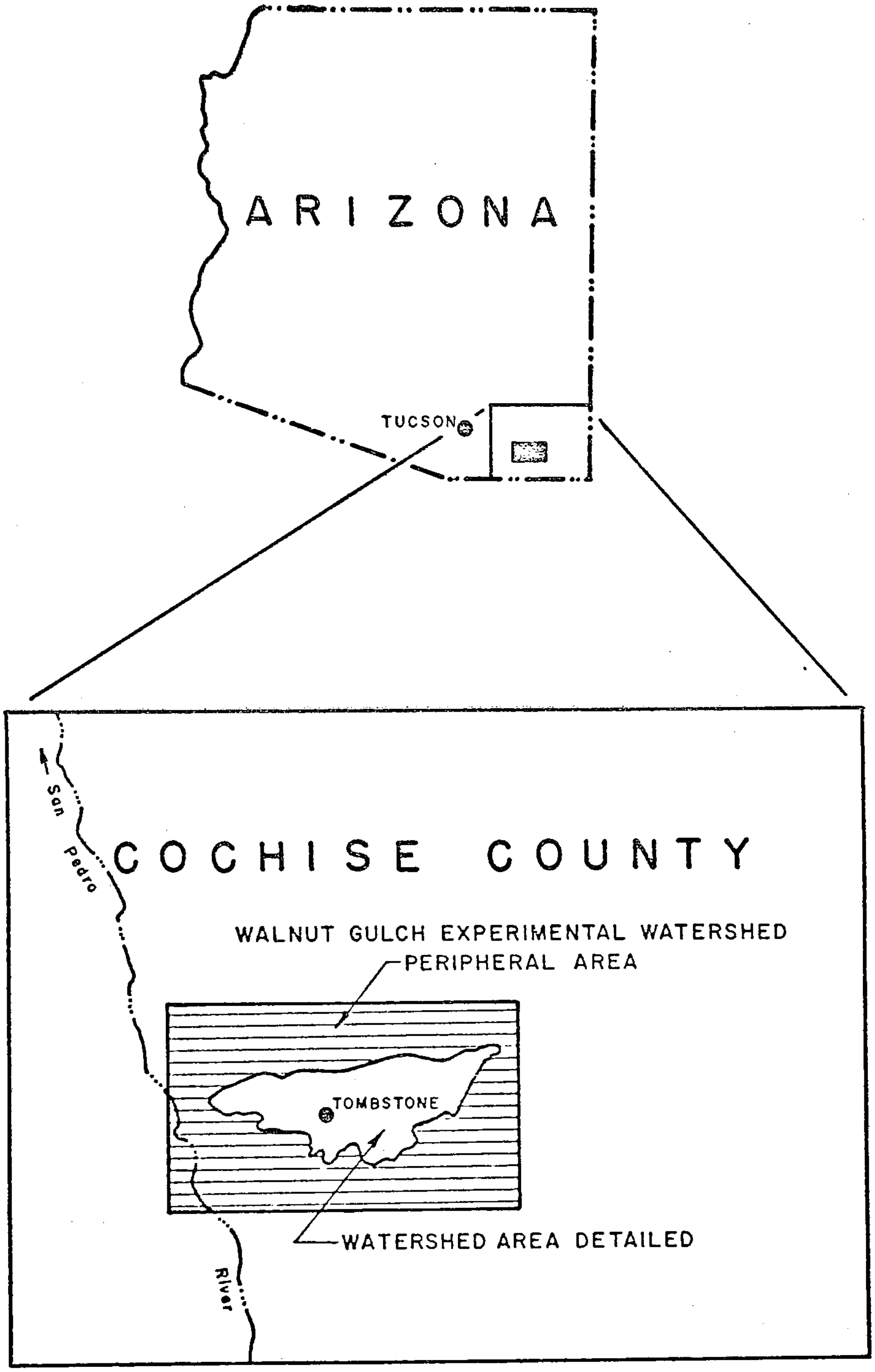

Fig. 3.1. Location of the Walnut Gulch Experimental Watershed near Tombstone, Arizona

feet at the outlet to slightly over 6,000 feet at the headwaters. Almost all runoff occurs from the natural grazed rangelands. There are relatively small amounts of urban runoff from the city of Tombstone.

Walnut Gulch was established by the Agricultural Research Service in 1953 to measure water yield from semiarid rangeland watersheds in the Southwest. A few recording and standard rain gages were set out in late 1953. In 1954 and 1955, five concrete shell structures were built to measure runoff in the ephemeral channels. As stated previously, Flume 1, with a drainage of 58 square miles, was constructed about two miles from the confluence with the San Pedro River. Flume 2, which drains about 36 square miles, was also built on the main stem of Walnut Gulch. Flume 3 (3-square-mile drainage), Flume 4 (560-acre drainage), and Flume 5 (8-square-mile drainage) were located on tributaries of Walnut Gulch within the 58-square-mile watershed (Fig. 3.2).

The structures were generally underdesigned, and by the end of 1955, all except Flume 4 had been totally or partially destroyed. Flume 1 was totally destroyed by the middle of the 1955 rainy season, and Flumes 2, 3, and 5 were badly damaged. The concrete shells were undermined, and all or partially washed out.

Because of this early experience, a permanent concrete flume-weir structure was designed expressly to measure runoff from the sediment-laden ephemeral streams of the Southwest. The first of these structures with about 10 times the previous capacity was built in 1958 replacing the badly damaged structure at Flume 3. In all, eleven of these flume-weirs have been built on the Walnut Gulch watershed (Figs. 3.3 and 3.4).

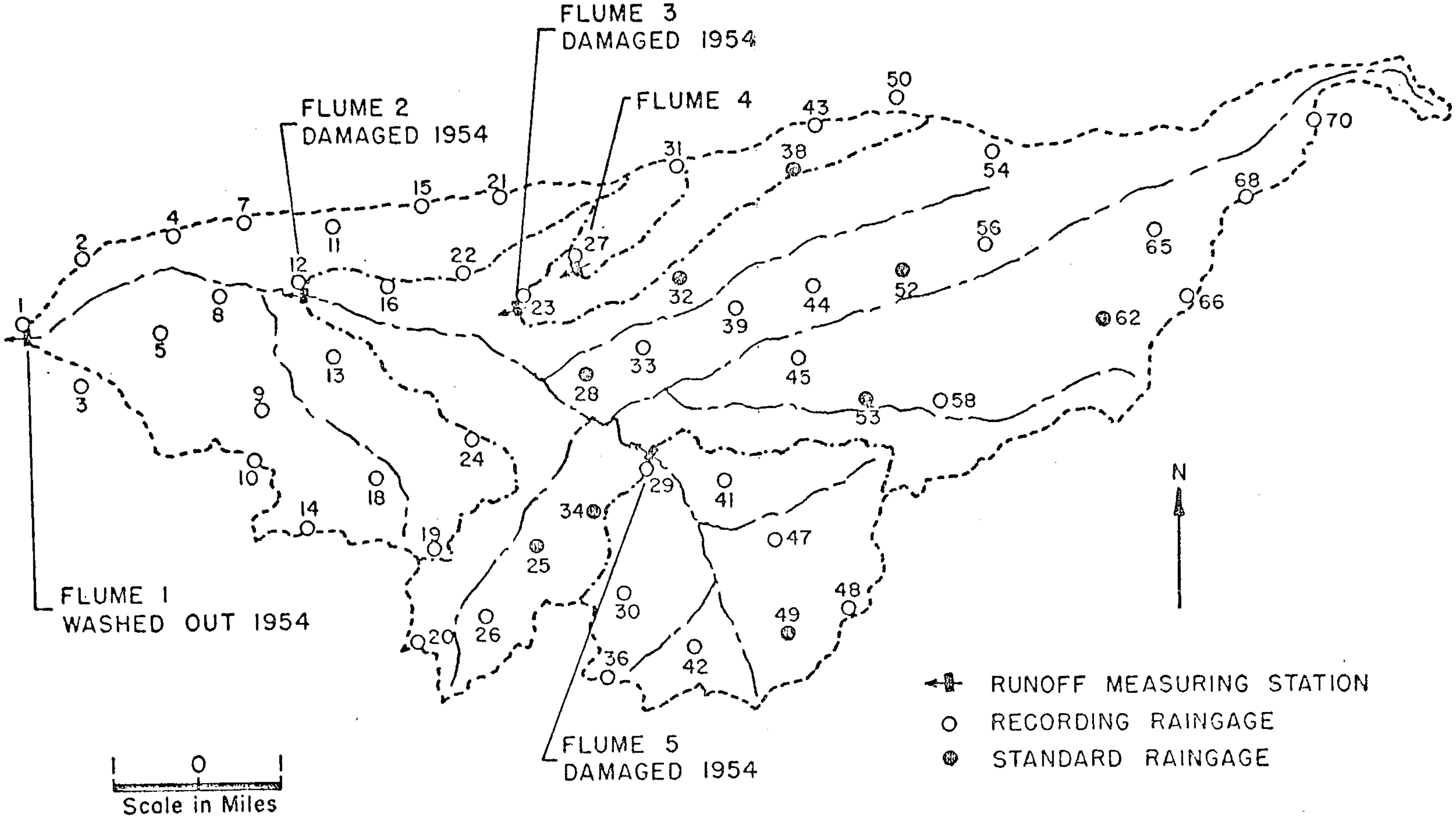

Fig. 3.2. Rain gage and flow measuring station (flume) location, Walnut Gulch, 1955

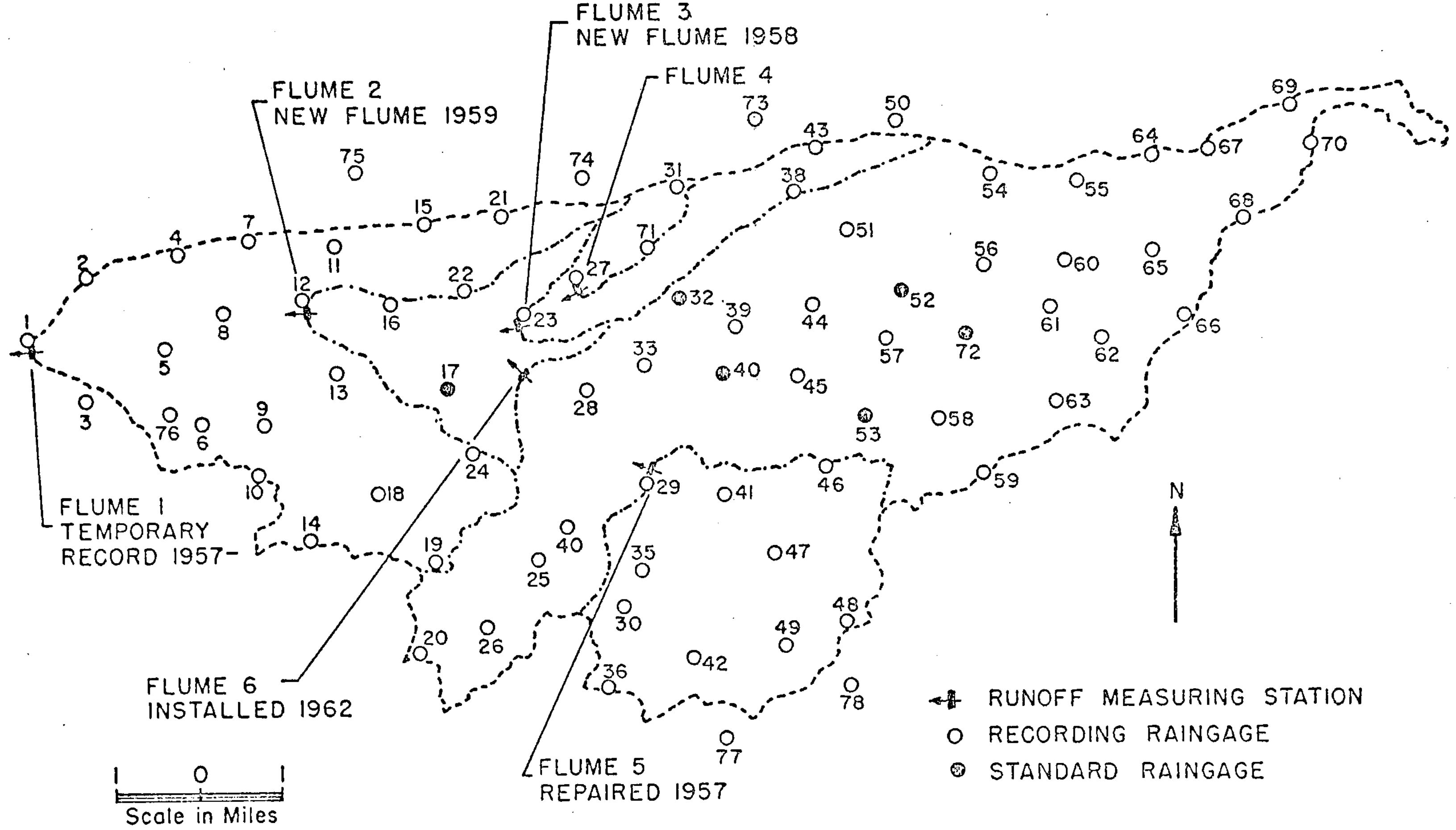

Fig. 3.3. Rain gage and flow measuring station (flume) location, Walnut Gulch, 1961

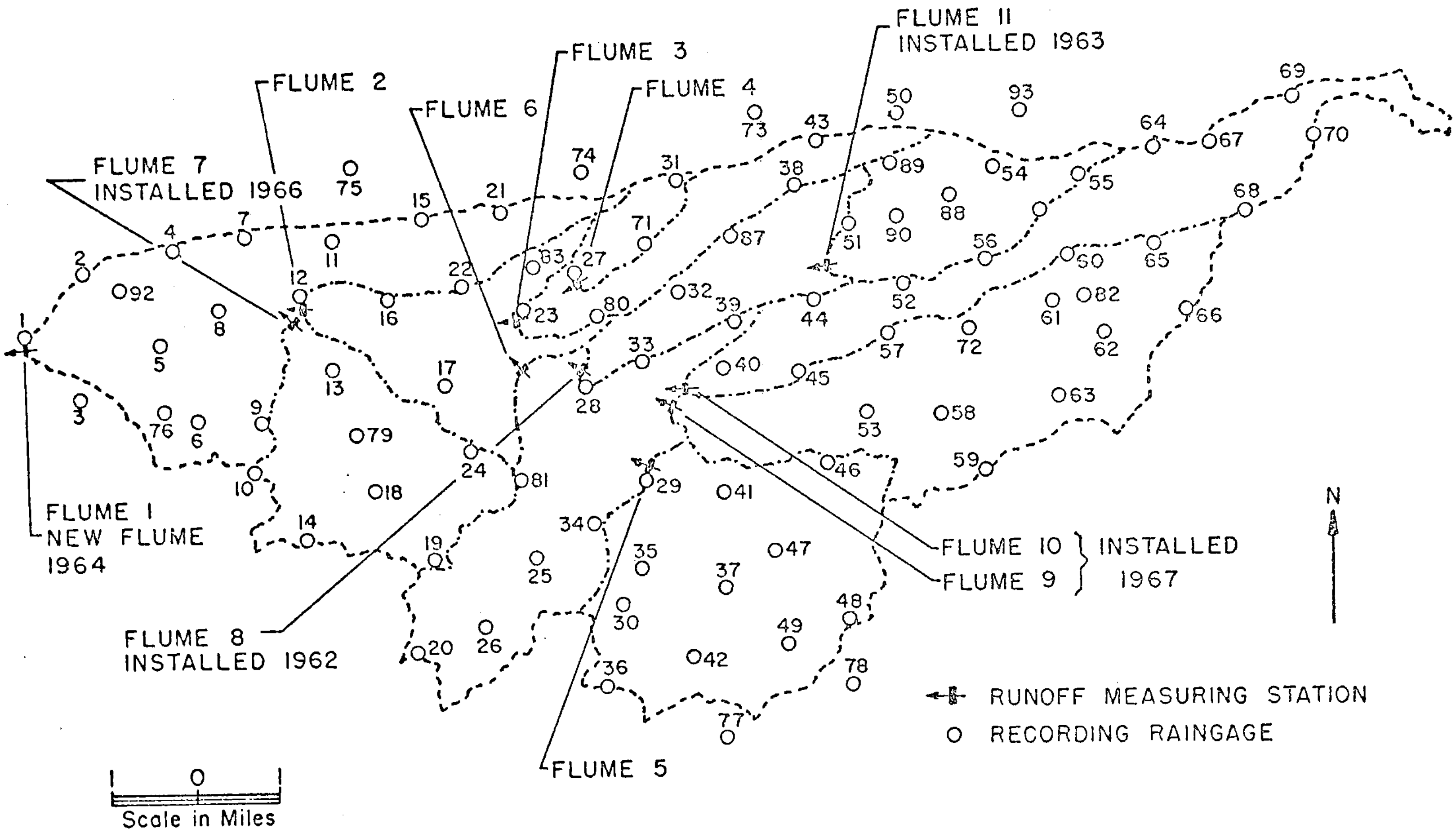

Fig. 3.4. Rain gage and flow measuring station (flume), Walnut Gulch, 1968

Records of peak discharge are available for all or part of the period from 1955 through 1969 at five stations on Walnut Gulch. Of these stations, only 4 and 5 provided continuous records for 15 years from one type of structure, but both these records were only fair. The runoff records at station 1 were very poor in 1954 and 1955, nonexistent in 1956, fair from 1957 through 1963 (a temporary station was established at 1 in 1957), and good from 1964 to the present. Ratings are presented here primarily to show differences in the quality of records between stations.

Records of peak discharge at station 2 were very poor from 1955 through 1957, nonexistent in 1958, poor in 1959 and 1960, and fair from 1961 to the present. For station 3, records were poor from 1955 through 1957, and good from 1958 to the present. In general, individual records on Walnut Gulch are classified about one degree lower than comparative U.S.G.S. classifications. In other words, good on Walnut Gulch would be excellent by U.S.G.S. standards, and so on. However, there are few U.S.G.S. records for watersheds as "small" as Walnut Gulch.

In general, the record is good for the stations that were established after 1960, but these records are relatively short. Obviously, the runoff records vary considerably in length of record and in accuracy of measurement. In this paper runoff records for Flumes 1, 3, 4, and 5 for the period 1955 through 1969 (15 years) were used to develop rainfall-runoff models and for frequency analyses. The record at Flume 2 was used to aid in estimating peak flows at 1 for the 1955 and 1956 seasons. Peak discharges at several stations for the storms of

July 22, 1964 and September 10, 1967 were used in estimating maximum flood peaks.

Originally, a network of about 60 recording rain gages was planned for the Walnut Gulch Experimental Watershed. Twenty-four weighing-type, 24-hour recording rain gages were placed on the lower and central parts of the watershed prior to the 1955 rainy season (Fig. 3.2). Because of limited funds, however, the network could not be completed at that time. Only a few gages were added to the network before the 1956 season, and the originally planned network was not completed until 1961. Several gages were placed outside the watershed boundary before the 1961 rainy season to facilitate isohyetal mapping of the summer thunderstorms (Fig. 3.3).

From 1961 to the present, recording rain gages have been added to fill obvious "gaps" in the network and for special studies on very small watersheds. In 1969 there were 95 weighing-type recording rain gages on or immediately adjacent to the Walnut Gulch watershed (Fig. 3.4). Of these, 91 were 24-hour recording rain gages; the other four were 6-hour gages.

Peak discharges are listed by rank for Stations 1, 5, 3, and 4 (Tables 3.1-3.4). In this study, all peak discharges were listed above 700 c.f.s., 300 c.f.s., 200 c.f.s., and 100 c.f.s. for 1, 5, 3, and 4, respectively.

Maximum peak discharges at Stations 1, 3, 4, and 5 were plotted in Figure 3.5. Maximum peak discharges were also plotted for three Walnut Gulch stations with seven or eight years of record--6, 11, and

Table 3.1. Peak discharge greater than 700 c.f.s. for watershed 1 (58 square miles), Walnut Gulch (1955-1969)

		Q	
Date	Time of peak	c.f.s.	*c.f.s. per acre
8-17-57	2200	11,500	0.340
8-02-57	1742	6,550	.194
7-19-55	2330	5,200	.154
7-22-64	2035	4,700	.139
9-10-67	1736	4,700	.139
8-22-61	1532	3,900	.115
8-16-58	2004	3,400	.106
8-14-58	1501	3,000	.089
7-22-55	1915	2,990	.088
9-10-64	0120	2,980	.088
7-26-55	0100	2,900	.086
9-11-64	2014	2,870	.085
7-20-55	1350	2,800	.083
7-26-59	2142	2,770	.082
8-19-63	1150	2,710	.080
9-07-63	2311	2,600	.077
8-25-63	2130	2,070	.061
8-17-61	2255	1,970	.059
8-31-63	1920	1,670	.049
8-07-69	1849	1,280	.038
8-08-57	1815	1,270	.038
8-14-66	1940	1.250	.037
7-21-59	1720	1,240	.037
8-22-63	1700	1,170	.035
7-26-62	0025	845	.025
9-08-64	2040	830	.025
8-23-58	2235	770	.023
9-24-62	1716	760	.022
9-04-62	1650	750	.022
9-04-65	1805	740	.022
7-29-62	2302	730	.022
8-19-66	1746	710	.021

*Based on an effective runoff-producing area of 33,800 acres.

Table 3.2. Peak discharges greater than 300 c.f.s. for watershed 5 (8.0 square miles), Walnut Gulch (1955-1969)

Date	Time of peak	Q c.f.s.	Q **c.f.s. per acre
*10-4-54	1950	5,300	1.293
8-17-57	2120	3,140	.766
7-26-59	2030	2,240	.546
8-08-47	1657	1,170	.285
8-10-55	2037	820	.200
8-31-68	1352	749	.183
8-31-63	1725	737	.180
8-19-66	1549	685	.167
8-16-58	1937	646	.158
8-21-58	2225	620	.151
8-03-67	1753	587	.143
7-19-56	0105	570	.139
9-08-57	1826	552	.135
8-19-63	1010	435	.106
9-04-65	1639	423	.103
7-25-62	2241	410	.100
8-09-55	0304	405	.099
8-14-58	1400	400	.098
8-02-57	1737	389	.095
9-08-64	2005	364	.089
7-31-61	1242	346	.084
7-20-59	2209	318	.078
7-07-67	1454	300	.073

*Station was established during 1954. Record not complete for 1954, but rainfall and runoff records available on Oct. 4, 1954.

**Based on an effective runoff-producing area of 4100 acres.

Table 3.3. Peak discharges greater than 200 c.f.s. for watershed 3 (3 square miles), Walnut Gulch (1955-1969)

		Q	
Date	Time of peak	c.f.s.	*c.f.s. per acre
7-19-55	2219	2,800	1.783
7-22-55	1745	1,800	1.146
8-16-58	1921	1,250	.796
7-26-55	0049	1,040	.662
7-20-55	1220	980	.624
8-17-61	2209	970	.618
7-25-55	1235	845	.538
8-14-58	1406	710	.452
9-10-64	0145	480	.306
8-23-58	2111	450	.287
8-16-64	1610	275	.175
7-22-64	2005	200	.127

*Based on an effective runoff-producing area of 1600 acres.

Table 3.4. Peak discharges greater than 100 c.f.s. for watershed 4 (560 acres), Walnut Gulch (1955-1969)

Date	Time of peak	Q c.f.s.	Q c.f.s. per acre
7-19-55	2214	1,270	2.268
7-22-55	1743	541	.966
7-26-55	0050	456	.814
8-17-61	2218	355	.634
7-25-55	1235	343	.612
7-20-55	1200	273	.490
8-3-55	1555	200	.357
7-31-55	1351	194	.346
8-16-58	1926	178	.318
8-14-58	1355	132	.236
7-28-55	1742	131	.234
8-17-57	2138	114	.203
7-22-64	1913	110	.196
9-10-64	0000	110	.196
7-29-56	0337	102	.182

K-1--for the storms of July 22, 1964. On the largest watershed, 1, the maximum peak discharge occurred August 17, 1957. The maximum peak discharge at 5, October 4, 1954, occurred when there were only two recording rain gages on the lower boundary of the watershed. The maximum flood peaks at Stations 3 and 4 (4 is a subwatershed of 3) resulted from a storm on July 19, 1955. The line sketched on Figure 3.5 indicates an apparent decreasing maximum flood peak per unit area with increasing watershed size for stations with 15 years of record. The maximum recorded peak discharge for watershed 11 appears to have a recurrence interval considerably longer than 15 years.

Peak discharges were plotted against recurrence intervals for 15 years of record for Watersheds 1, 3, 4, and 5 (Fig. 3.6). Lines were drawn through the 4 sets of values simply to tie the points together for easier visual inspection. Runoff between July 20 and August 3, 1955 was not included for 1, 3, and 4, since the record was extremely poor for these watersheds during this period. Eliminating this period did not appreciably affect the calculations for Watershed 1. Furthermore, since by far the highest peak discharge in 1955 for stations 1, 3, and 4 occurred on July 19, the first day of the "wet" period, eliminating the "wet" period would not affect calculations for annual maximum peak discharge.

Expected annual maximum peak discharges were determined for selected recurrence intervals of 10, 25, 50, and 100 years for Watershed 1 from several standard statistical distributions--Hazen, normal, log-normal, Gumbel, and log-Gumbel. Also, the log Pearson Type III method which has been recommended for standard use by Federal agencies

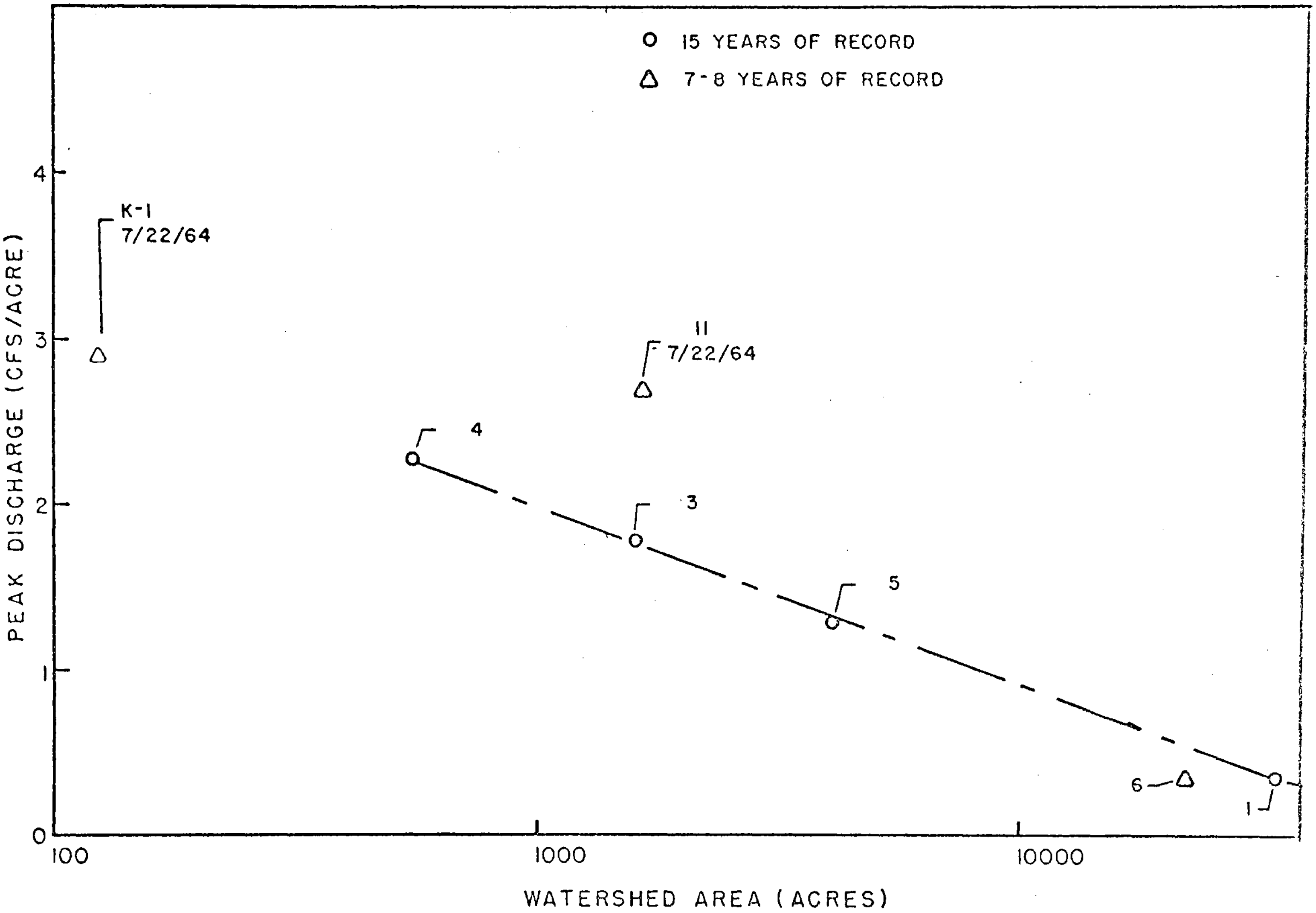

Fig. 3.5. Maximum peak discharge versus watershed area, Walnut Gulch, Arizona (1955-1969)

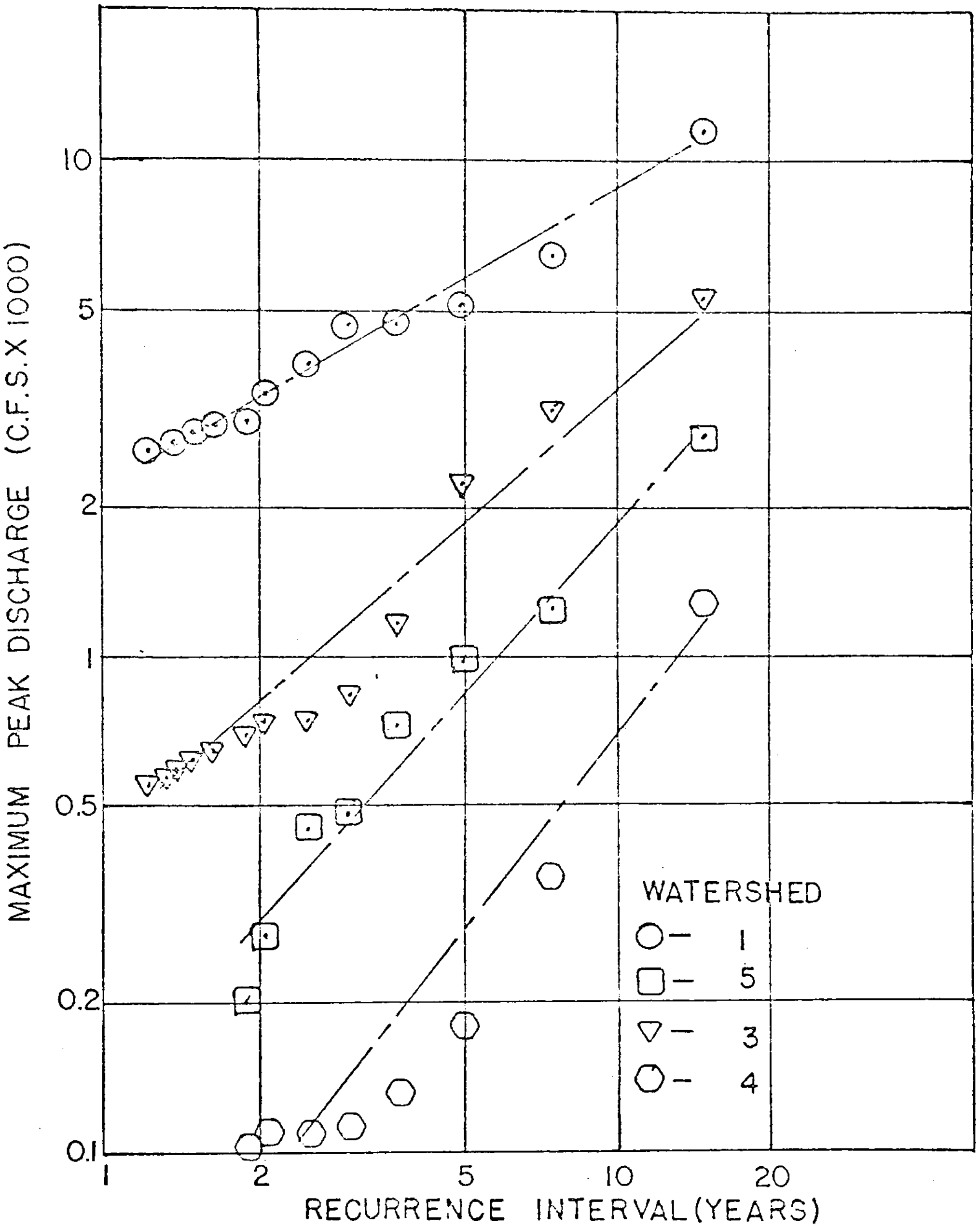

Fig. 3.6. Maximum peak discharge versus recurrence intervals for 4 Walnut Gulch watersheds

was used to calculate peak discharges for recurrence intervals of 10, 25, 50, and 100 years. For the log Pearson Type III method,

Y = Arithmetic magnitude of an annual flood event.

X = Logarithmic magnitude of Y.

N = Number of events in the record being used = 15 (for Walnut Gulch)

M = Mean of the X's = 3.31

x = X-M

S = Standard deviation of the X's = 0.40

g = Skew coefficient = 0.17

K = Pearson Type III coordinate from Table 1, Bull. 15 for recurrence intervals of 10, 25, 50, and 100 years = 1.30, 1.82, 2.16, and 2.47, respectively

Q = Computed peak discharge for 10, 25, 50, and 100 years = 7,000, 11,000, 15,000, and 20,000 c.f.s., respectively.

Curves for the six methods are shown in Figures 3.7-3.9, and peak discharges for 10-, 25-, 50-, and 100-year recurrence intervals, as determined by the 6 methods are presented in Table 3.5. Interestingly enough, the Hazen method, which was first proposed in 1914, appeared by eye to fit the distribution of values as well as, or better than, the other 5 methods.

All six methods are based on infinite statistical distributions in which the chance of occurrence is always greater than zero no matter how great the prediction. For 100 years the range of estimated peak discharge was 15,000 to 35,000 c.f.s. If recurrence intervals are required for longer periods, as often is the case, the range of predicted values would be much greater. The problem of predicting peak discharges from short periods of record is illustrated by an arithmatic plot of Q

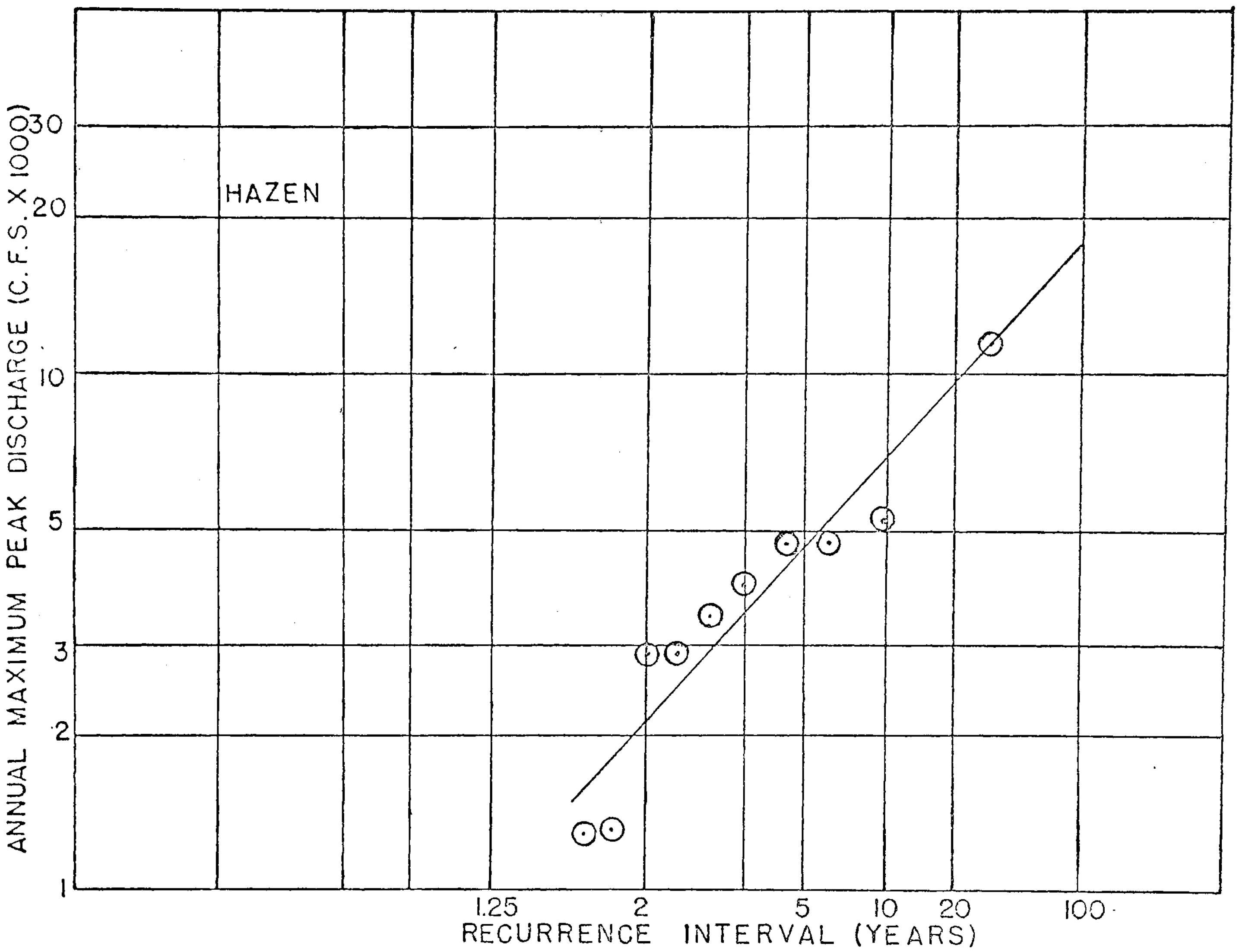

Fig. 3.7. Annual maximum peak discharge versus recurrence interval for Walnut Gulch 1, Hazen

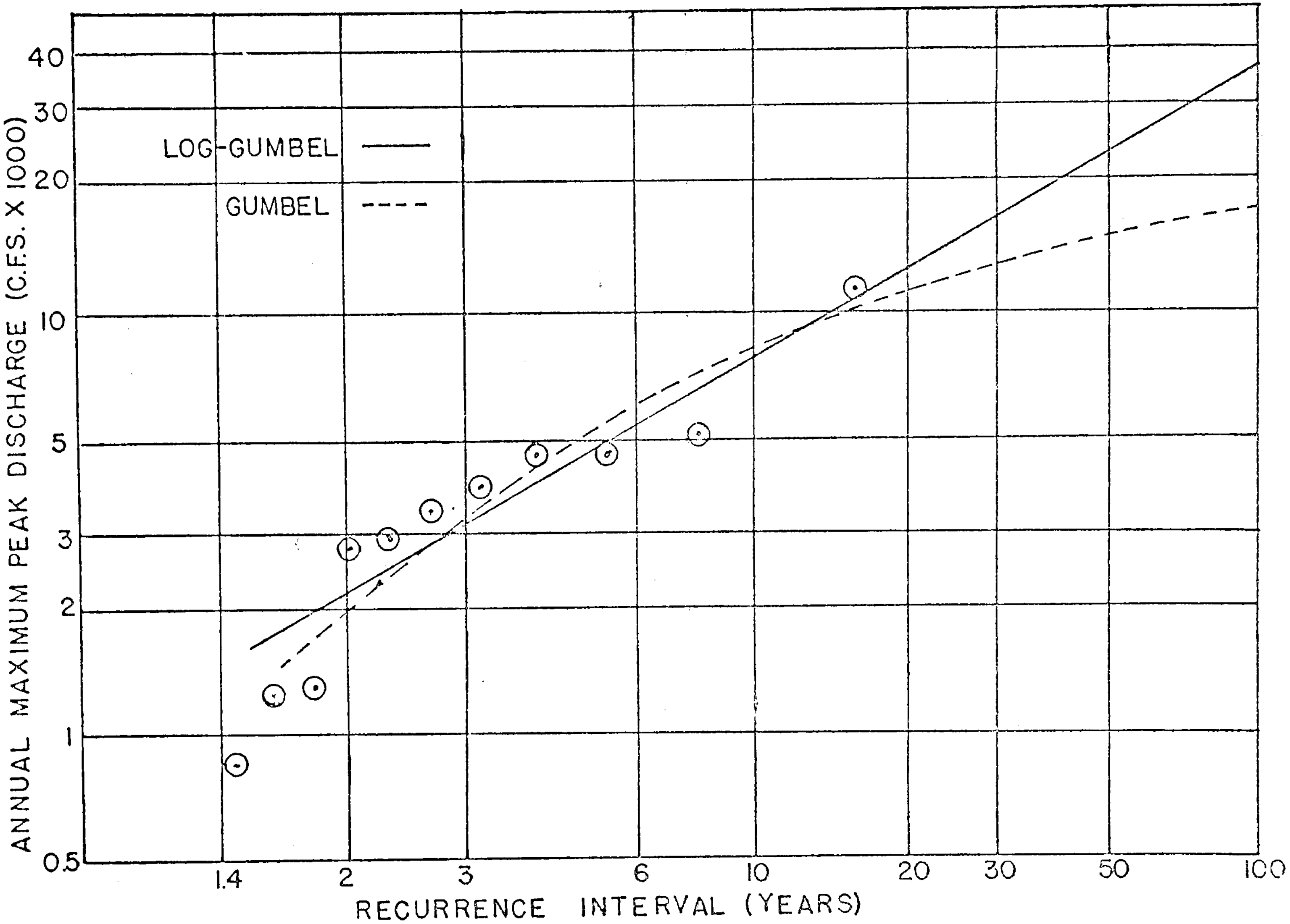

Fig. 3.8. Annual maximum peak discharge versus recurrence interval for Walnut Gulch 1, Gumbel

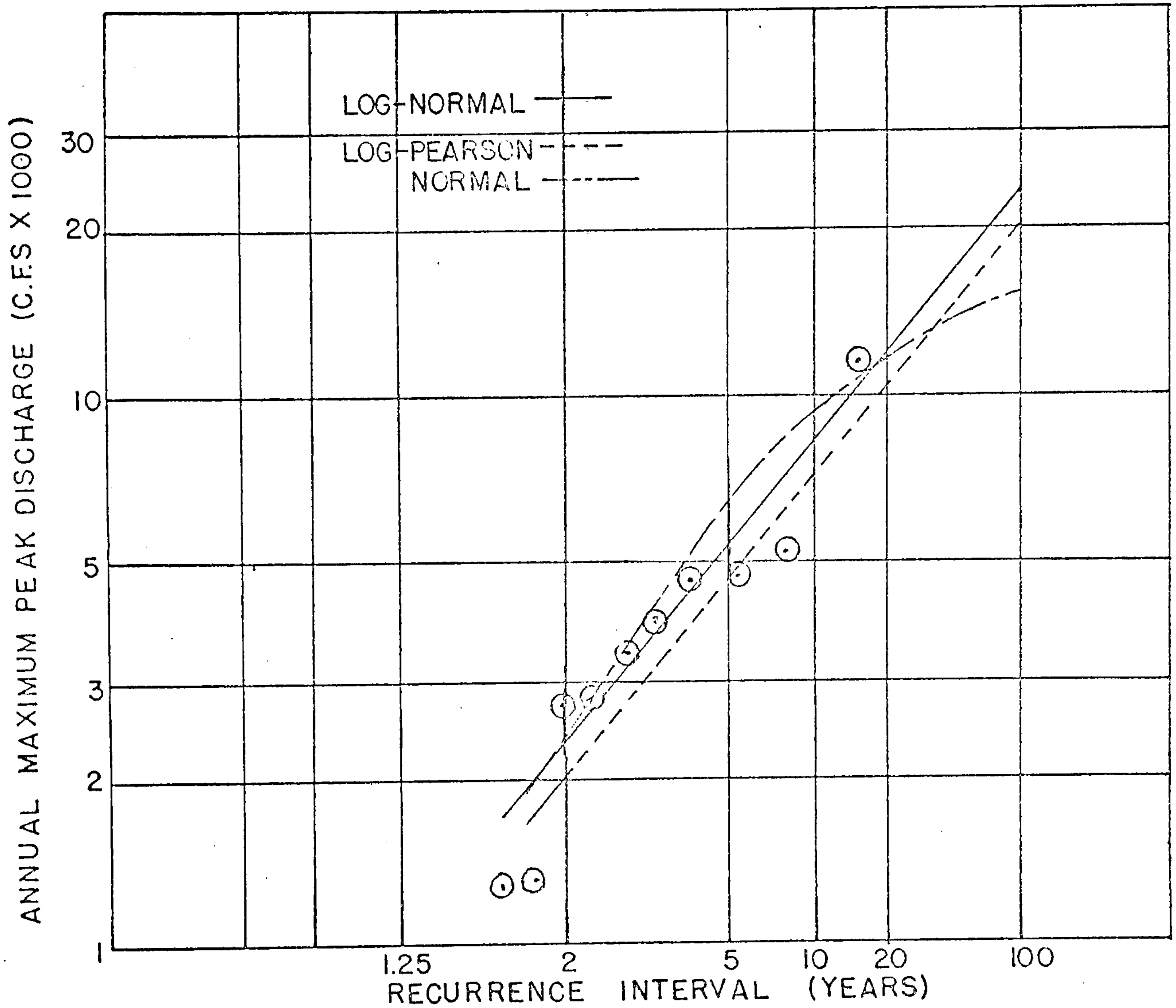

Fig. 3.9. Annual maximum peak discharge versus recurrence interval for Walnut Gulch 1, normal

Table 3.5. Comparison of estimated peak discharge (c.f.s.) for watershed 1 on Walnut Gulch by six standard methods

Method	Recurrence Interval (years) 10	25	50	100
Hazen	7,000	10,500	14,000	18,000
Normal	9,500	12,000	13,500	15,000
Log-Normal	8,000	13,000	17,000	23,000
Gumbel	8,500	12,00	14,500	17,000
Log-Gumbel	8,000	14,000	23,000	35,000
Log-Pearson Type III	7,000	11,000	15,000	20,000

versus recurrence interval for several distributions for Walnut Gulch 1 (Fig. 3.10). The known values are clustered in the lower left-hand corner of the plot. Extrapolations to even the 50-year flood cover far more distance than the complete range of known values. Obviously, slight initial differences in the fit of the known values is magnified with increasing recurrence interval.

Finally, the method described by Patterson and Somers (1966) is included for comparison with the six statistical methods. From extrapolation of curve 21 on Figure 17 in Water Supply Paper 1683 to a smaller area, the mean annual flood for the 58-square-mile Walnut Gulch watershed was 2,300 c.f.s. From Figure 2, Curve C, the ratios of peak discharge to mean annual flood for 10, 20, and 50 years were 2.3, 3.2, and 4.4, respectively, and expected peak discharges were 5,000 c.f.s., 7,500 c.f.s., and 10,000 c.f.s., respectively (Fig. 3.11). By extrapolation, the 100-year storm would be 12,500 c.f.s. For Walnut Gulch, the U.S.G.S. method appeared to underestimate the magnitudes for given recurrence intervals.

As stated by Patterson and Somers, use of the curves is not recommended for recurrence intervals of greater than 50 years or for watersheds of less than 100 square miles (for southeastern Arizona).

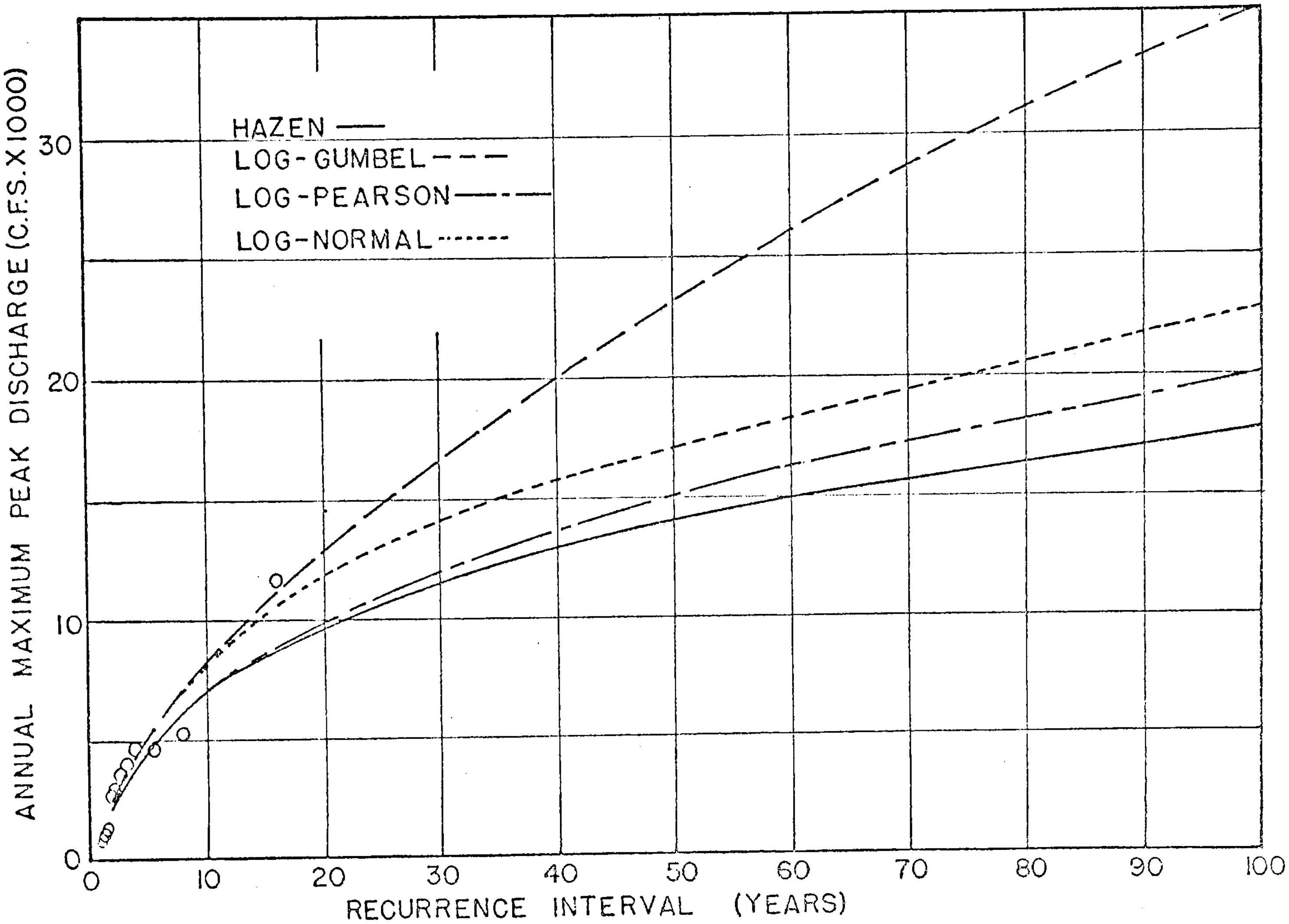

Fig. 3.10. Annual maximum peak discharge versus recurrence interval for selected distributions, Walnut Gulch, Arizona

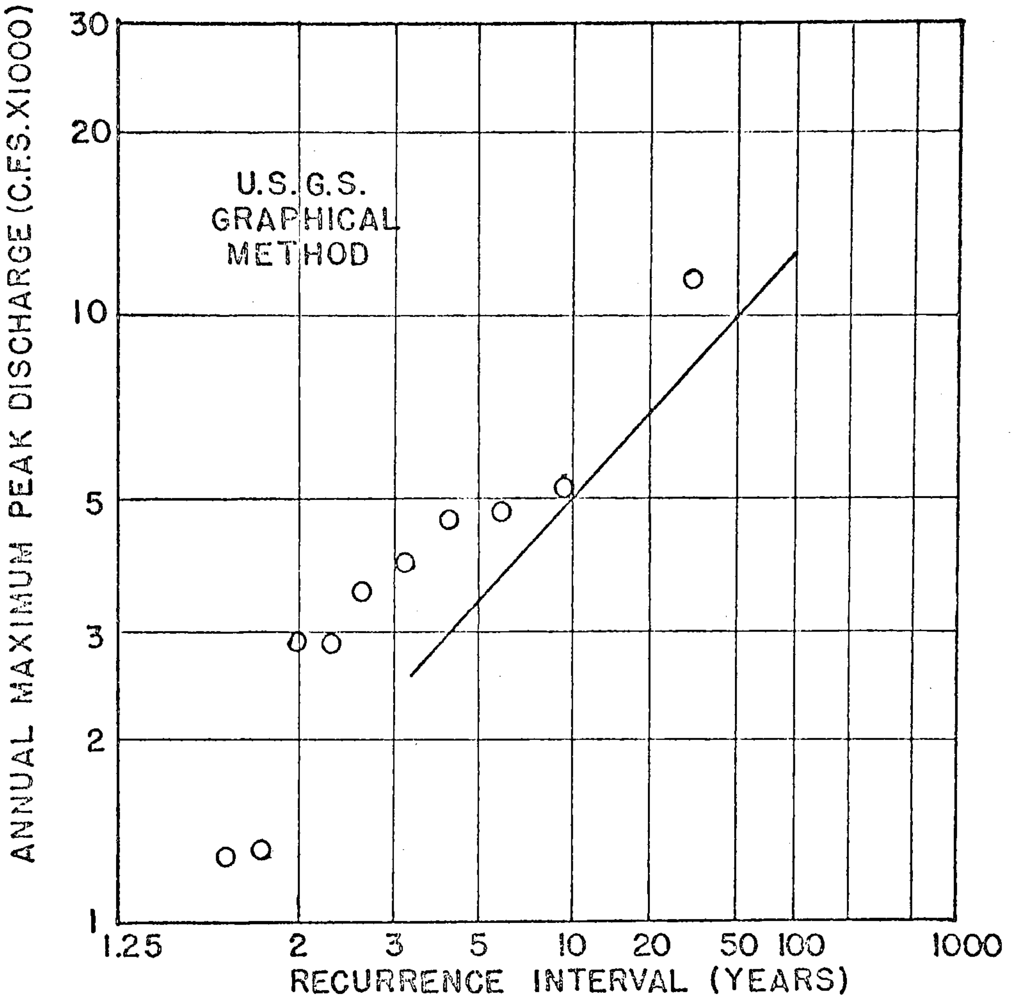

Fig. 3.11. Annual maximum peak discharge versus recurrence interval for Walnut Gulch using U.S.G.S. graphical method

CHAPTER 4

THUNDERSTORM RAINFALL-RUNOFF MODELS

Because there are more rainfall records than runoff records, and because rainfall is supposedly much less affected by watershed characteristics, those who must estimate runoff look with a hungry eye at rainfall. In order to convert rainfall data into runoff estimates there must be a relationship between the two--a model in today's parlance. Such a model is of necessity a simplified model of physical reality, because reality is too complex and too unknown.

Woolhiser (1970) quoted Rosenblueth and Wiener (1945):

> No substantial part of the universe is so simple that it can be grasped and controlled without abstraction. Abstraction consists in replacing the part of the universe under consideration by a model of similar but simpler structure. Models, formal or intellectual on the one hand, or material on the other, are thus a central necessity of scientific procedure (p. 7.1).

Rainfall-Runoff Relationships

The complexities of rainfall-runoff relationships on semiarid rangeland watersheds are illustrated in Figure 4.1. The hydrographs represent what might be expected first from uniform rainfall on a hypothetical watershed, then with increasing realism in both the watershed model and rainfall input, and finally from thunderstorm rainfall on a 60-square-mile rangeland watershed such as Walnut Gulch.

First, a theoretical watershed of about 60 square miles, similar to Walnut Gulch, with the time of concentration on the order of

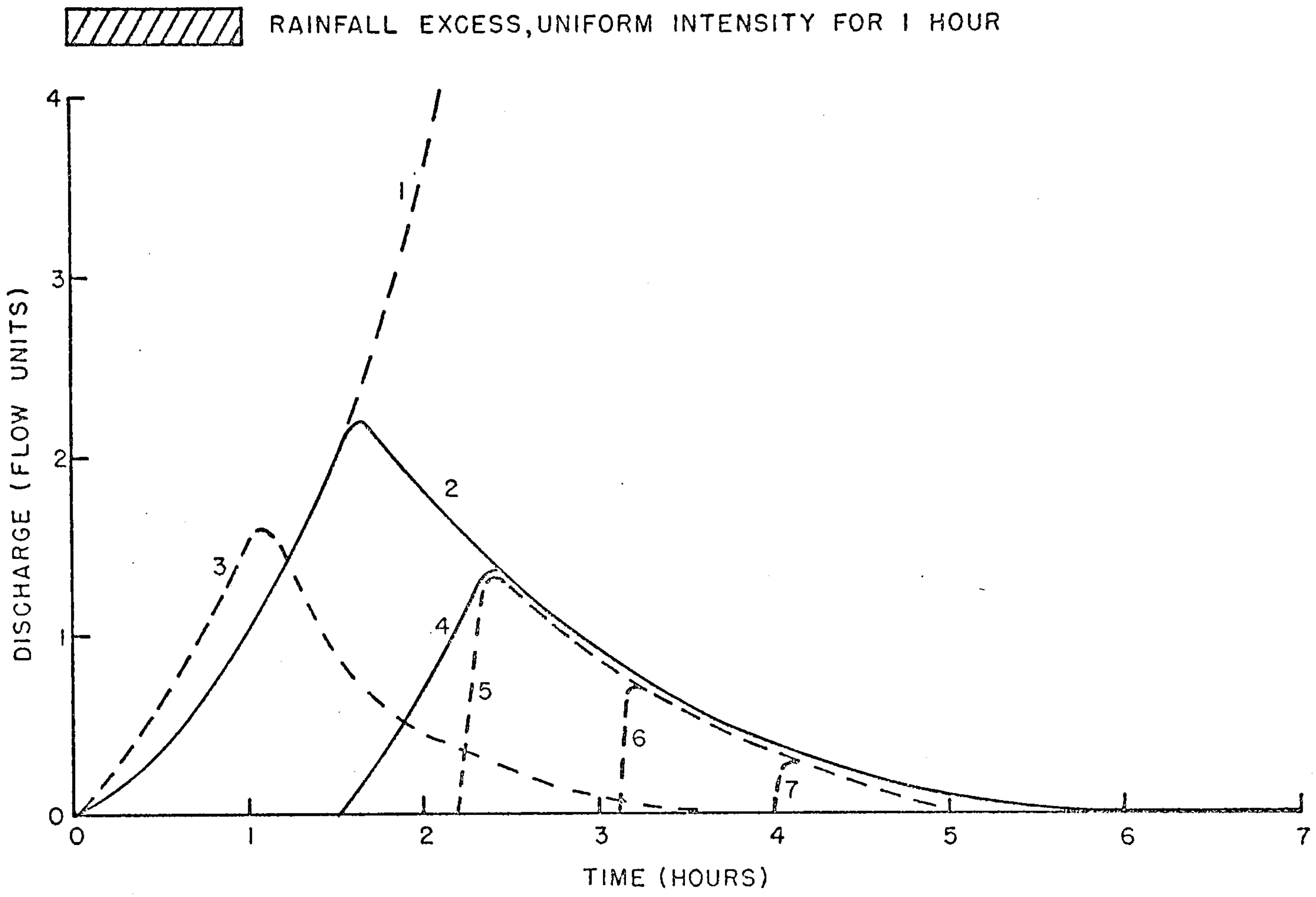

Fig. 4.1. Descriptive hydrographs for a semiarid rangeland watershed of approximately 60 square miles

4 hours was assumed. Slope of the principal channels was about 1 percent. Channel abstractions were part of the watershed losses before rainfall excess in the theoretical application, and rainfall excess was uniform both in space and time over the entire watershed. If rainfall excess continued at the same rate indefinitely, an equilibrium condition would be approached after about 4 hours. If the system were linear, an S-curve would result. The lower part of the S-curve is shown as the dashed line identified by the numeral 1.

If rainfall ceased after one hour and was assumed uniform over the watershed, Hydrograph 2 might result.

A more realistic, but still idealized, situation occurs if runoff-producing rainfall covers only part of the watershed. If the upper half of the watershed were covered with uniform rainfall for one hour, and the runoff were measured at a station at the lower edge of the runoff-producing storm, Hydrograph 3 might result. Primarily because of the reduced watershed size and time of concentration, the rising limb of Hydrograph 3 would be expected to be steeper than for Hydrograph 2. If runoff as represented by Hydrograph 3 were routed from the upper station to the watershed outlet without channel abstractions, Hydrograph 4 would result. Because of channel storage, Hydrograph 4 would be expected to have a longer base and lower peak than Hydrograph 3, although the volume of runoff would be the same under both hydrographs.

To add more realism to the problem, the channel abstractions between the upper and lower stations were included in the next step, while still assuming that runoff-producing rainfall (rainfall excess) occurred only on the upper half of the watershed. The steep rising limb of Hydrograph 5 results from the channel abstractions; there would also be smaller but significant abstractions in the recession limb of the hydrograph. In Hydrograph 5, peak discharge was not reduced appreciably, since it was assumed that there was enough discharge in the rising limb of Hydrograph 4 to satisfy most of the channel abstractions.

Hydrographs 6 and 7 more closely resemble what might actually be measured at the watershed outlet. These hydrographs would result from either shorter durations of the same intensity rainfall on the upper part of the watershed, from runoff-producing rainfall (uniform rainfall excess) covering less than 1/2 of the watershed, or some combination of the two. Actually, on many occasions, channel flows in the upper reaches of the watershed do not reach the watershed outlet.

Quantitative analysis of the thunderstorm rainfall-runoff relationship illustrated here is extremely difficult for several reasons. For one thing, rainfall is not uniform in time or space, and rainfall input can only be estimated from rainfall measurements within certain limits of accuracy and precision. Furthermore, peak discharge does not increase proportionally to rainfall intensity. Also, channel abstractions may account for much or all of the initial onsite runoff. For example, thunderstorm runoff from the 58-square-mile Walnut Gulch watershed is only about 7 percent of thunderstorm rainfall.

However, it should be possible to develop models and possibly establish frequencies for major runoff events. The more intense longer lasting thunderstorms produce a core, or pulse, of runoff-producing rainfall. Reich and Hiemstra (1965) estimated flood peaks from maximum

30-minute rainfall. Fogel (1968) and Bell (1969) and others suggested that flood peaks from small watersheds may be best correlated to short-duration rainfall, but did not suggest exact durations. Osborn and Lane (1969) found that peak discharges on very small watersheds (11 acres and less) were best correlated to the maximum 15-minute rainfall. Bell (1969) also stressed that using average intensities rather than rainfall depths for given durations, could be misleading. Furthermore, in the Rational Formula, runoff is based on rainfall for the time of concentration, and the time of concentration increases with increasing watershed size. In general, the required duration for runoff-producing rainfall should increase with increasing watershed size for very small watersheds where the peak runoff is correlated to the rainfall of duration equal to the time of concentration. If a shorter rainfall duration can be enough greater, the relationship is not so simple.

The direction that the storm moves, or propagates, and the location of the storm center should affect both the magnitude and the time of the peak discharge. However, observations of real events indicate that storm direction and location (assuming that the storm is largely contained within the watershed) may not be a significant factor for peak discharges from the larger runoff-producing events. The greatest abstractions occur with the advancing flood front and the wave fronts of later contributions move more rapidly through the already wetted channels. Therefore, the contributions from the subwatersheds from the same storm tend to accumulate as one peak at the watershed outlet. The magnitude of this peak seems to be relatively unaffected by the order in which runoff from each subwatershed enters the main channel. Also, as suggested by comparing hydrographs 4 and 5 in Figure 4.1, channel abstractions from major storms centered well upstream from the measuring station are accounted for largely in the rising limb of the hydrograph, and there is no measurable difference in the peak discharge between a storm located just above the stations and well upstream.

To illustrate the extreme variability in rainfall-runoff relationships on the Walnut Gulch watershed, peak discharges were plotted versus maximum 30-minute point rainfall depths for all storms that produced peak discharges of more than 700, 300, 200, and 100 c.f.s. for Watersheds 1, 5, 3, and 4, respectively (Figs. 4.2-4.5). Watershed 2 was not included because of generally poor records, and 6 was not included because of a shorter period of record. These storms were the major runoff events from each of the four watersheds. The correlation between peak discharge and the maximum 30-minute point rainfall was very poor, but did suggest increasing peak discharge with increasing rainfall.

Regression Models

Based on the discussion earlier in this chapter and some preliminary trials, the maximum 30-minute rainfall measured at individual points within the runoff-producing area of each storm was chosen as the best rainfall variable for correlating rainfall and runoff for watersheds of 1 to 58 square miles.

Peak discharge was chosen as the dependent variable, because only peak records were available from some of the "record" storms during the early years of record. Although it might be more appropriate to correlate volume of rainfall with volume of runoff, Diskin and Lane

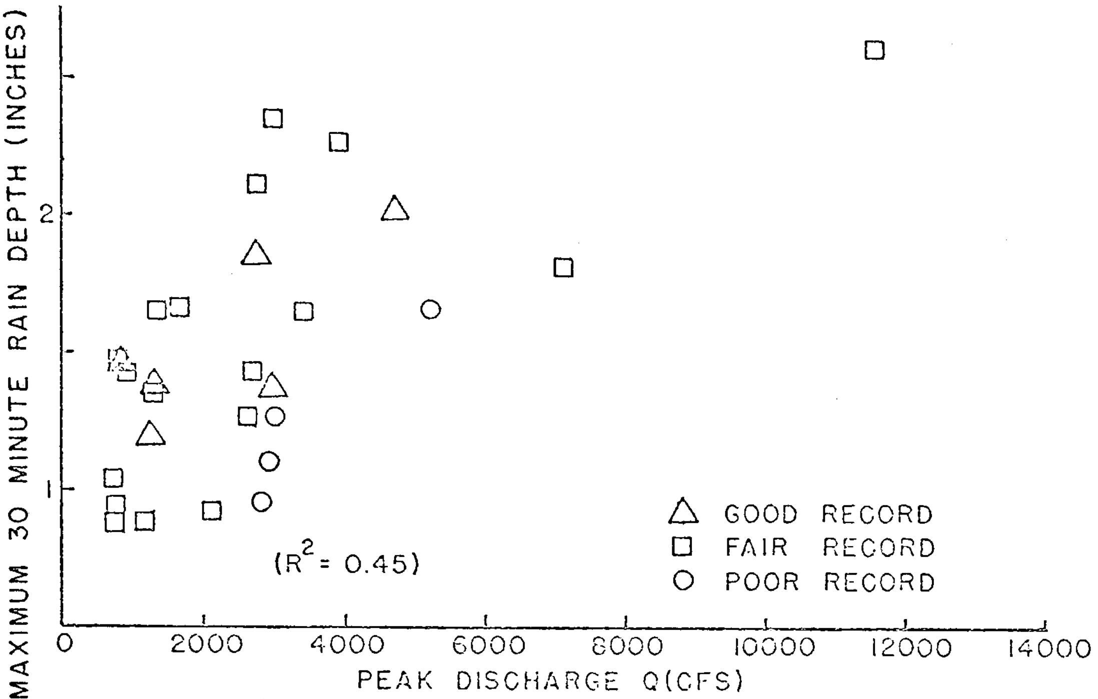

Fig. 4.2. Maximum 30-minute storm rainfalls versus peak discharges, Walnut Gulch 1, 1955-1969

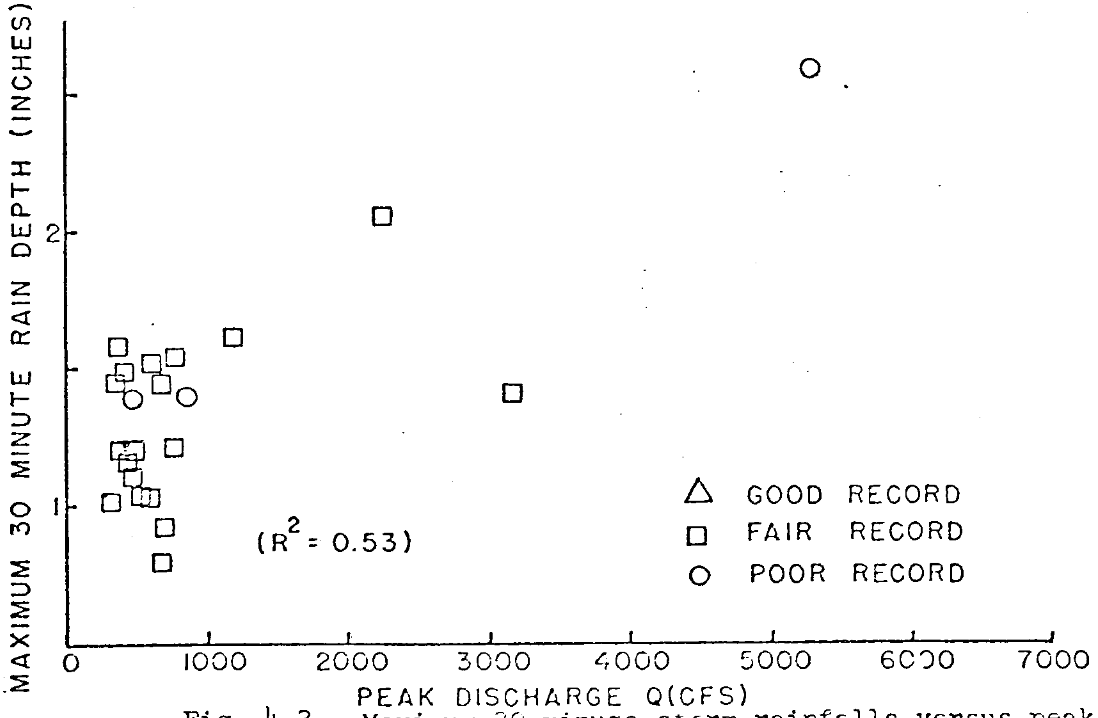

Fig. 4.3. Maximum 30-minute storm rainfalls versus peak discharges, Walnut Gulch 5, 1955-1969

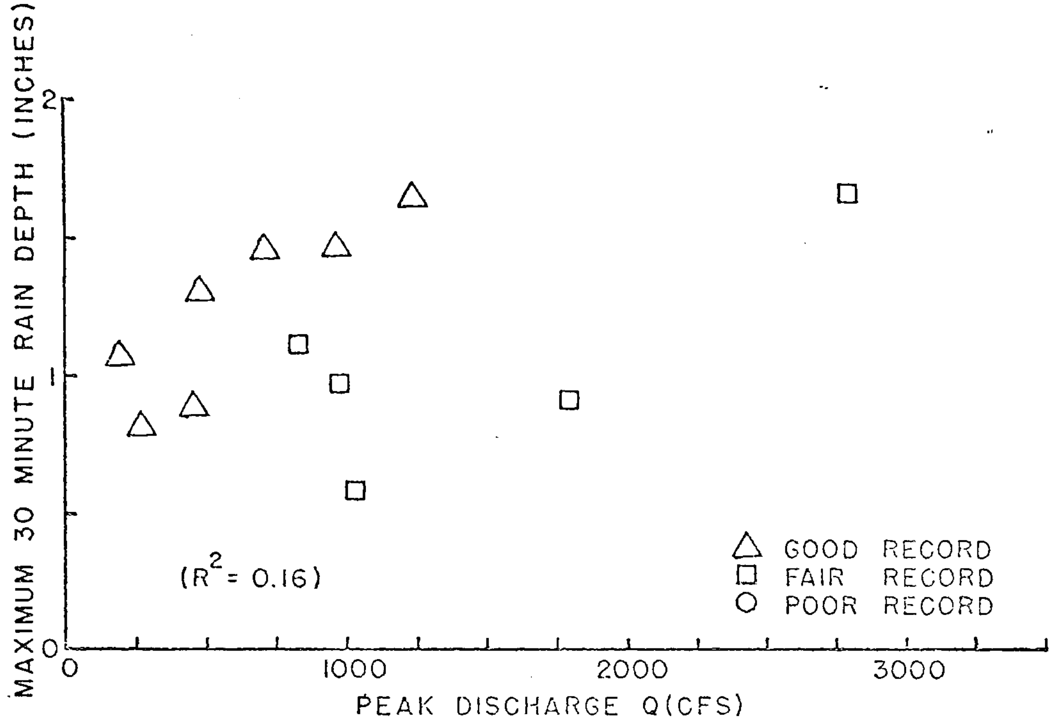

Fig. 4.4. Maximum 30-minute storm rainfalls versus peak discharges, Walnut Gulch 3, 1955-1969

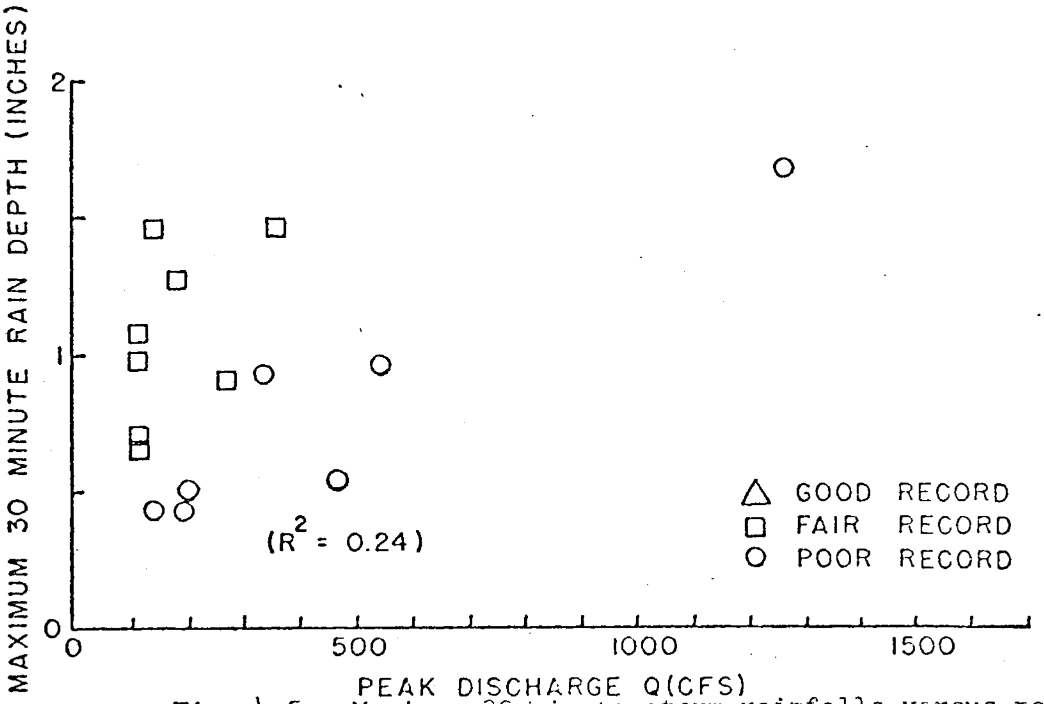

Fig. 4.5. Maximum 30-minute storm rainfalls versus peak discharges, Walnut Gulch 4, 1955-1969

(1970) found that there is high correlation between peak and volume of runoff on Walnut Gulch, and therefore rainfall volume could be directly correlated to peak discharge.

Because of previous good experience of Schreiber and Kincaid (1967) and Osborn and Lane (1969), a stepwise multiple linear regression program (MLR) was utilized to correlate rainfall and runoff variables. The dependent variables were peak discharge in c.f.s. (Q) and c.f.s./acre (Q_a). The regression formulas that were developed were generally based on Q_a, since discharge per unit area indicated the large decrease of runoff per unit area with increasing watershed size.

In the MLR program the basis of best fit by least squares is indicated by R^2. Mendenhall (1963) defined R^2, the coefficient of determination, as "the ratio of the reduction in the sum of squares deviations obtained by using the linear model to the total sum of squares of deviations about the sample mean, $\bar{y}$, which would be the predictor of y if x were ignored." The means are heavily biased by a preponderence of "low" values for thunderstorm runoff. Therefore, deviations from the means are much less for "low" values than for "high" values, and the linear model will be influenced much more strongly by one, or a few, high runoff peaks than by a larger number of lower peak discharges. This is advantageous for models predicting maximum peak discharges, as long as the high peaks are "good" records. The standard error of estimate of Q_a was also determined as an indication of the standard deviation of estimated values.

Initially several input variables were included in the regression analyses. The most important, maximum 30-minute rainfall volume, was broken down into estimated volumes between the 0.5-, 1.0-, 1.5-, 2.0-, and 2.5-inch isohyets (V_{05}, V_{10}, V_{15}, V_{20}, and V_{25}, respectively). Rainfall values were calculated in square-mile inches per 30 minutes. Other variables that were included in the first regression equation were the maximum 30-minute point rainfall depths for 1-, 2-, and 3-gage averages ($1P_{30}$, $2P_{30}$, and $3P_{30}$, respectively), the distances from the stream flow measuring station to the center and nearest edge of runoff-producing rainfall (D_{cent} and D_{edge}), and an antecedent runoff index (ARI).

The following series of trials illustrates the development of the models for peak discharge on Walnut Gulch. The trials are described as they were made.

First Trial

For Trial No. 1, the antecedent runoff index was calculated on the basis of the number of previous significant runoff events and the time of incidence of these events during the nine days prior to the given event. Runoffs during the previous 24, 48, 72, 96, 120, 144, 168, 192, and 216 hours were assigned values of 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, and 0.1, respectively. The antecedent index for each designated flood event was the addition of antecedent runoff values from the nine days prior to the event. For example, if significant runoffs were recorded 2 and 4 days before the designated storm, the ARI would be 0.8 + 0.6, or 1.4.

All rainfall variables were included in correlating rainfall and runoff on Walnut Gulch 1. Since there were no storms in which the maximum 30-minute depths exceeded 2.0 inches on watersheds 3 and 4, V_{20} and V_{25} were not used for correlation on these two watersheds. Also, only the single maximum 30-minute rainfall ($1P_{30}$) and the distance to the nearest edge of runoff-producing rainfall D_{edge} were used on W-3 and W-4. All variables except $3P_{30}$, D_{cent}, and D_{edge} were used on W-5.

For 1, the largest watershed, the rainfall variable that best explained the variability in peak runoff was the volume of rainfall for depths of rainfall greater than 2.0 inches (V_{20}). The coefficient of determination, R^2, for the rainfall-peak runoff correlation using only Q_a and V_{20} was 0.61. By adding a second variable, V_{10}, the correlation was improved with R^2 equal to 0.73. By adding a third significant variable, V_{25}, R^2 was raised to 0.79. The equations were

$$Q_a = 0.058 + 0.032\ V_{20}, \qquad (4.1)$$

$$Q_a = 0.034 + 0.005\ V_{10} + 0.022\ V_{20}, \qquad (4.2)$$

and

$$Q_a = 0.033 + 0.006\ V_{10} + 0.043\ V_{25} - 0.003\ V_{20}. \qquad (4.3)$$

Equations 4.1 and 4.2 made sense; Equation 4.3 did not. In all analyses using MLR programs, one must check computer results for reasonableness. Quite often, meaningless equations such as Equation 4.3 do occur. Also, the coefficients in the regression equations may not have physical meaning.

For 5, the second largest watershed, the input variable that best explained the variability in runoff was again V_{20}, and the input variable that most improved the initial equation was again V_{10}. The third best variable, $2P_{30}$, did not significantly improve the equation.

The resulting significant equations were

$$Q_a = 0.167 + 0.287\ V_{20}, \text{ and} \qquad (4.4)$$

$$Q_a = 0.054 + 0.208\ V_{20} + 0.062\ V_{10}. \qquad (4.5)$$

For Equations 4.4 and 4.5, R^2 was 0.75 and 0.87, respectively. These equations were definite improvements over similar equations for watershed 1.

For 3, the third largest watershed, the single input that best defined the variability between rainfall and peak runoff was V_{15}. For the simple regression equation R^2 was 0.66. By adding V_{05}, the correlation was improved, with R^2 equal to 0.78. When a third variable, D_{edge}, was added, R^2 was 0.87. The fourth variable added to the correlation did not significantly improve the regression equation. The equations for watershed 3 with 1, 2, and 3 significant input variables were

$$Q_a = 0.489 + 0.001V_{15}, \qquad (4.6)$$

$$Q_a = 0.018 + 0.001V_{05} + 0.001V_{15}, \qquad (4.7)$$

and

$$Q_a = 0.151 + 0.001V_{05} + 0.001V_{15} - 0.204D_{edge}. \qquad (4.8)$$

All 3 equations appeared reasonable, since V_{05} and V_{15} should affect runoff positively, and D_{edge} should affect it negatively.

For 4, the smallest watershed, V_{15} also best explained the variability in runoff with R^2 equal to 0.79. The next 3 variables that were added each improved the correlation with R^2 increasing about 0.05 for each, which was barely significant. By adding ARI, V_{10}, and V_{05}, in that order, R^2 was 0.84, 0.89, and 0.93. Because of poor rainfall records for earlier events, only the simple equation

$$Q_a = 0.414 + 0.002\ V_{15} \qquad (4.9)$$

was meaningful.

In comparing the results for the four watersheds, apparently V_{20} for watersheds 1 and 5 and V_{15} for watersheds 3 and 4 were the most significant input variables of those chosen for the analysis. Furthermore, adding V_{10} to the equation for 1 and 5, and V_{05} for 3, improved the correlations significantly. Only on 4 was antecedent runoff theoretically a significant variable.

Therefore, either antecedent channel conditions are not a factor in correlating rainfall and runoff peaks on Walnut Gulch, or the available data and method of analysis do not identify the effects of antecedent runoff. Possibly, the poorer correlations for rainfall and runoff for watershed 1 than for 5 could be partially explained by the increased importance of antecedent channel conditions. At any rate, antecedent runoff is an essential part of rainfall-runoff relationships for smaller runoff events, so further analysis was undertaken.

The actual estimated values for runoff peaks as calculated by the MLR program in the first trial are shown in Tables 4.1-4.4. Because of the relatively small sample sizes, the estimated peaks are based on the same storms from which the equations were developed. These are the estimated values for the equations with all variables added. They did not represent the values as estimated from only the significant input variables.

Using Equation 4.2 for watershed 1 and Equation 4.5 for watershed 5, estimated peaks were determined for the listed major runoff

Table 4.1. Major estimated versus actual peak discharges for watershed 1, Walnut Gulch, 1955-1969

Date	Rank	Actual (c.f.s./acre)	Estimated (c.f.s./acre)	Deviation
19-07-55	3	.154	.158	-.004
29-07-55	12	.083	.028	.055
22-07-55	8	.088	.064	.024
26-07-55	10	.086	.063	.023
02-08-57	2	.194	.171	.023
08-08-57	19	.038	.032	.006
17-08-57	1	.340	.336	.004
14-08-58	8	.089	.083	.005
16-08-58	7	.106	.097	.009
23-08-58	25	.023	.039	-.016
21-07-59	21	.037	.044	-.007
26-07-59	13	.082	.110	-.028
22-08-61	6	.115	.112	.003
26-07-62	23	.025	.047	-.022
29-07-62	29	.022	.041	-.019
04-09-62	27	.022	.033	-.011
24-09-62	26	.022	.018	.004
19-08-63	14	.080	.057	.023
22-08-63	22	.035	.066	-.031
25-08-63	16	.061	.042	.019
31-08-63	17	.049	.031	.018
07-09-63	15	.077	.037	.040
22-07-64	4	.139	.110	.029
08-09-64	24	.025	.051	-.026
10-09-64	9	.088	.073	.014
11-09-64	11	.085	.088	-.003
04-09-65	28	.022	.053	-.031
14-08-66	20	.037	.056	-.019
19-08-66	30	.021	.038	-.017
10-09-67	5	.139	.154	-.015
07-08-69	18	.038	.077	-.039

Table 4.2. Major estimated versus actual peak discharges for watershed 5, Walnut Gulch, 1955-1969

Date	Rank	Actual (c.f.s./acre)	Estimated (c.f.s./acre)	Deviation
*04-10-54	1	1.293	1.293	.000
09-08-55	17	.099	.065	.034
10-08-55	5	.200	.211	-.011
19-07-56	12	.139	.255	-.116
02-08-57	19	.095	.179	-.084
08-08-57	4	.285	.192	.093
09-08-57	13	.135	.170	-.035
17-08-57	2	.766	.569	.197
14-08-58	18	.098	.078	.020
16-08-58	9	.158	.123	.035
21-08-58	10	.151	.100	.051
20-07-59	22	.078	.162	-.084
26-07-59	3	.546	.546	.000
31-07-61	21	.084	.011	.073
25-07-62	16	.100	.152	-.052
19-08-63	14	.106	.136	-.030
31-08-63	7	.180	.105	.075
08-09-64	20	.089	.293	-.204
04-09-65	15	.103	.139	-.036
19-08-66	8	.167	.058	.109
07-07-67	23	.073	.097	-.024
03-08-67	11	.143	.084	.059
31-08-68	6	.183	.246	-.063

*Station installed during 1954 season.

Table 4.3. Major estimated versus actual peak discharges for watershed 3, Walnut Gulch, 1955-1969

Date	Rank	Actual (c.f.s./acre)	Estimated (c.f.s./acre)	Deviation
19-07-55	1	1.783	1.722	.061
20-07-55	5	.624	.559	.065
22-07-55	2	1.146	.822	.324
25-07-55	7	.538	.454	.084
26-07-55	4	.662	.838	-.176
14-08-58	8	.452	.468	-.016
16-08-58	3	.796	1.009	-.213
23-08-58	10	.287	.445	-.158
17-08-61	6	.618	.574	.044
22-07-64	12	.127	.026	.101
16-08-64	11	.175	.259	-.084
10-09-64	9	.306	.335	-.029

Table 4.4. Major estimated versus actual peak discharge for watershed 4, Walnut Gulch, 1955-1969

Date	Rank	Actual (c.f.s./acre)	Established (c.f.s./acre)	Deviation
19-07-55	1	2.268	2.268	.000
20-07-55	6	.497	.381	.116
22-07-55	2	.966	.802	.164
25-07-55	5	.612	.533	.079
26-07-55	3	.814	.728	.086
28-07-55	11	.234	.455	-.221
31-07-55	8	.346	.288	.058
03-08-55	7	.357	.234	.123
29-07-56	15	.182	.243	-.061
17-08-57	12	.203	.191	.012
14-08-58	10	.236	.341	-.105
16-08-58	9	.318	.589	-.271
17-08-61	4	.634	.499	.135
22-07-64	13	.196	.086	.110
10-09-64	14	.196	.417	-.221

events. Estimated and actual peaks were then compared in Figures 4.6 and 4.7. The deviation for estimated values varies about 0.05 c.f.s./acre for 1. For 5, the estimated value for the second largest event on record was approximately 0.3 c.f.s./acre feet too low. Otherwise the comparison between estimated and actual peaks was quite good. The second largest event also had the "wettest" antecedent channel condition of any of the large peaks, and the first and third peaks occurred after relatively dry periods, so the larger ARI for the second largest peak decreased the spread between estimated and actual peak discharges.

Second Trial

Only data from watersheds 1 and 5 were used for Trial No. 2. Since the maximum 30-minute depths of rainfall did not significantly improve the rainfall-peak runoff correlations in Trial No. 1, only $1P_{30}$ was retained as an input variable in Trial No. 2. Also, both the antecedent runoff index and the maximum 30-minute volumes of rainfall were calculated differently.

For antecedent channel conditions, each runoff event during the season was assigned a value equal to the peak discharges divided by 1,000. At the same time, an estimate of channel "losses" was assigned for each day without runoff. The values for each day without runoff, representing rough estimates of losses in evaporation, transpiration, and percolation from the upper channel alluvium were 0.8 and 0.1 for 1 and 5, respectively. In other words, main channels on Walnut Gulch can extract much more water from flows than do the channels on watershed 5. The ARI was calculated for each major event by adding the

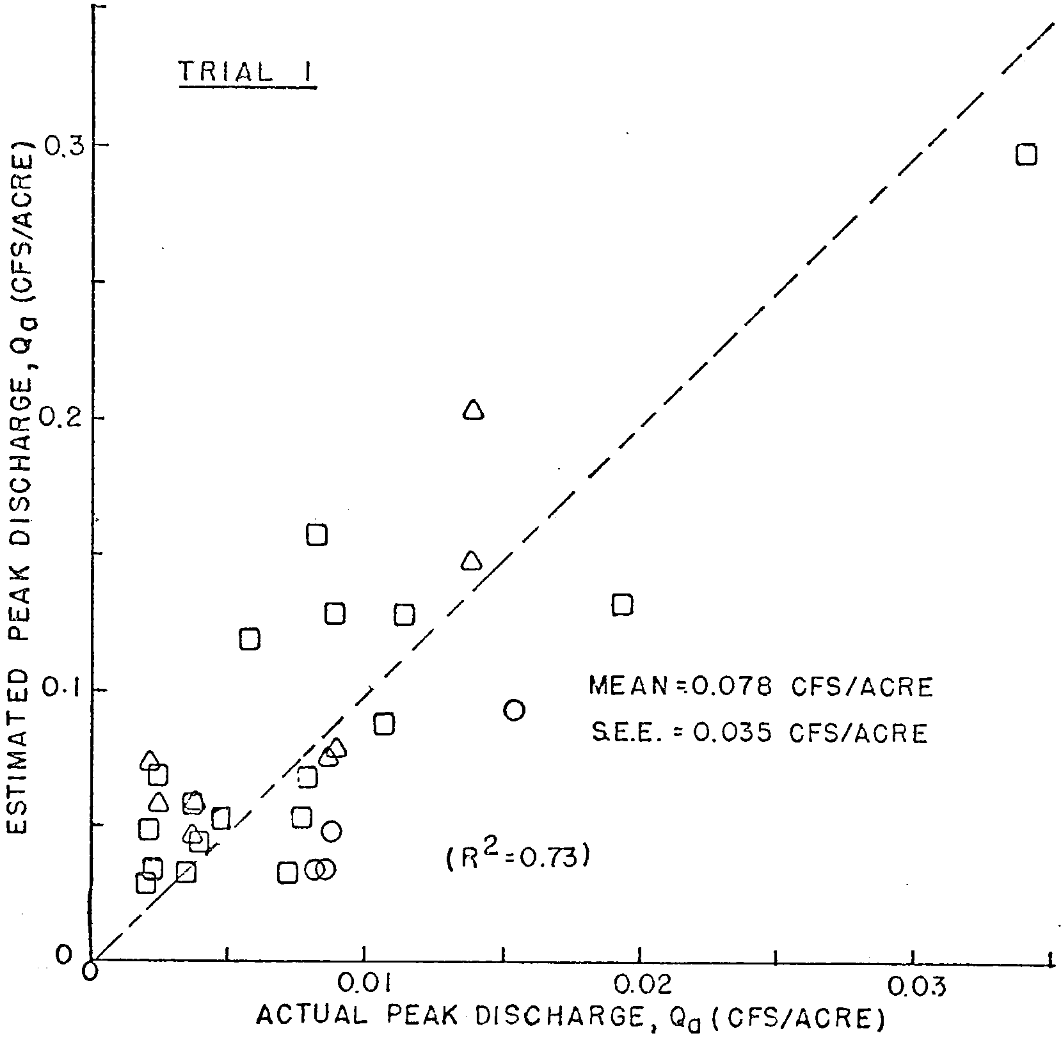

Fig. 4.6. Predicted (Equation 2) versus actual peak discharges, Walnut Gulch 1, 1955-1969

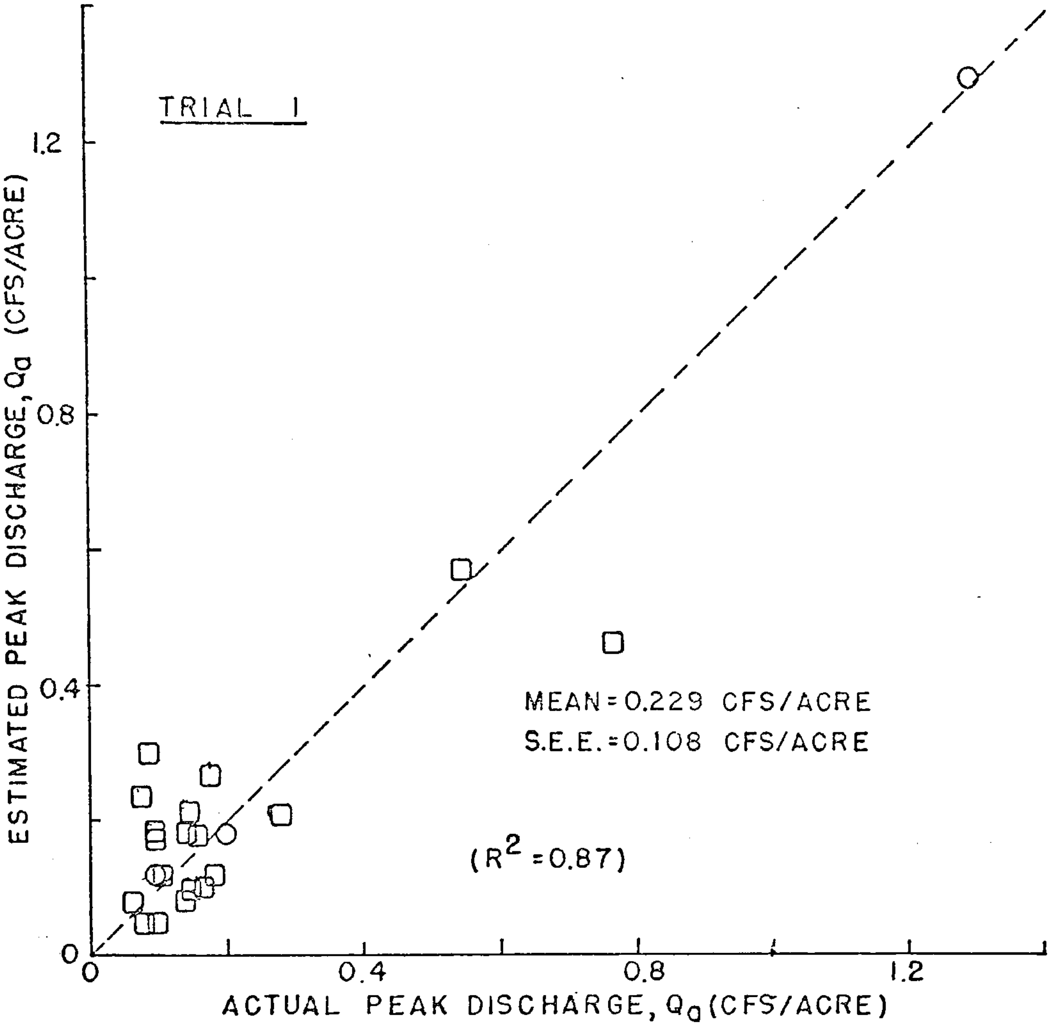

Fig. 4.7. Predicted (Equation 5) versus actual peak discharges, Walnut Gulch 5, 1955-1969

previous runoff values and subtracting the assumed losses continuously through each rainy season, with the limitation that the ARI could not be negative.

Maximum 30-minute volumes of rainfall were changed slightly to represent a better estimate of the actual volume of rainfall between each pair of isohyets. Each added level of rainfall should contribute a larger percent of its volume to streamflow. For example, a greater percentage of V_{10} as compared to V_{05} should contribute to channel flows, since much of V_{05} should go to satisfying surface retention, detention, and infiltration capacities, as well as providing the transmission losses in the smaller channels.

As was expected, V_{20} was still the single variable which best explained the variability of runoff on 1 and 5, and adding V_{10} still most improved the initial correlation between Q_a and V_{20}.

For watershed 1, the regression equation for Q_a correlated with V_{10} and V_{20} was

$$Q_a = 0.036 + 0.095\ V_{20} + 0.008\ V_{10}, \tag{4.10}$$

with an R^2 of 0.72. For Q_a and V_{20} alone, R^2 was 0.61. Therefore, adding V_{10} significantly improved the regression equation.

With ARI added, the equation became

$$Q_a = 0.019 + 0.095\ V_{20} + 0.010\ V_{10} + 0.007(\mathrm{ARI}). \tag{4.11}$$

Adding ARI further improved the correlation significantly with R^2 increasing to 0.79. Also, the coefficients for the variables seemed reasonable.

The coefficient of 0.007 for ARI appeared reasonable. For the largest ARI of record, about 12, the added contribution to the peak discharge would be about 0.08 c.f.s./acre, which is roughly 25 percent of the maximum peak discharge of 11,500 c.f.s. (0.34 c.f.s./acre). This would have added about 3,000 c.f.s. on August 17, 1957. The ARI for August 17, 1957 calculated by the method described on the previous page was zero.

The estimated peak discharge for the maximum event of record, August 17, 1957, using Equation 4.11, was 0.30 c.f.s./acre.

When a fourth variable was added, V_{25}, R^2 increased to 0.82, which was not a statistically significant improvement in the correlation. However, the resulting equation (4.12) was reasonable and gave a better estimate of the maximum peak discharge. Also, the coefficient for ARI was still reasonable.

$$Q_a = 0.019 + 0.018V_{20} + 0.012V_{10} + 0.172V_{25} + 0.006(ARI) \quad (4.12)$$

The predicted peak for August 17, 1957 from this equation was 0.335, which is essentially identical to the actual peak of 0.340.

The estimated versus actual peak discharge as computed from Equations 4.11 and 4.12 are shown in Figures 4.8 and 4.9, respectively. Equation 4.12 gave a better estimate of the maximum peak discharge for the period of record and seemed to be better than Equation 4.11 for estimating the lesser peak discharges as well.

For 5, antecedent channel conditions also improved the rainfall peak runoff correlations significantly. The values of R^2 were 0.75, 0.86, and 0.92 for one, two, and three variables, respectively. These variables were V_{20}, V_{10}, and ARI, in that order of significance.

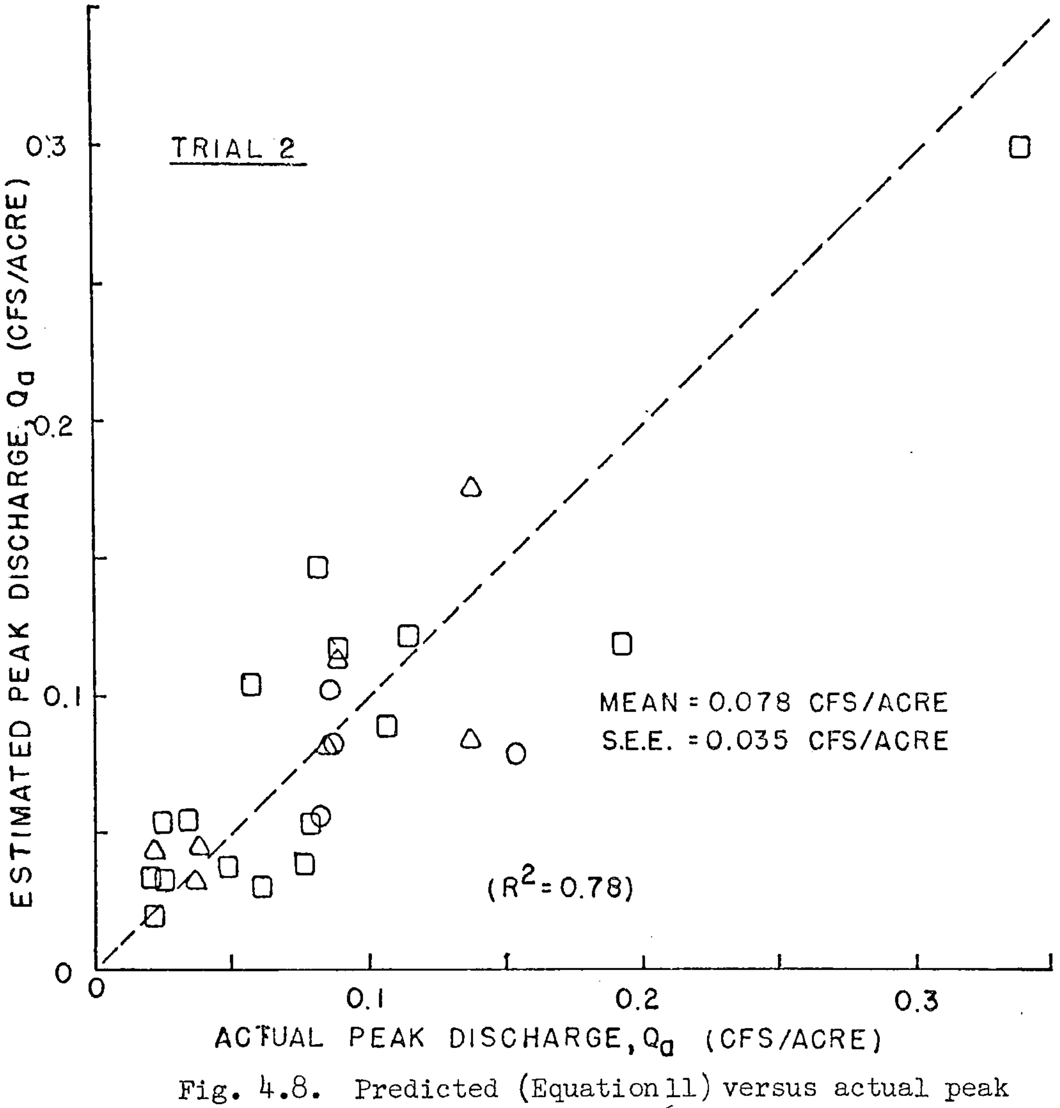

Fig. 4.8. Predicted (Equation 11) versus actual peak discharges, Walnut Gulch 1, 1955-1969

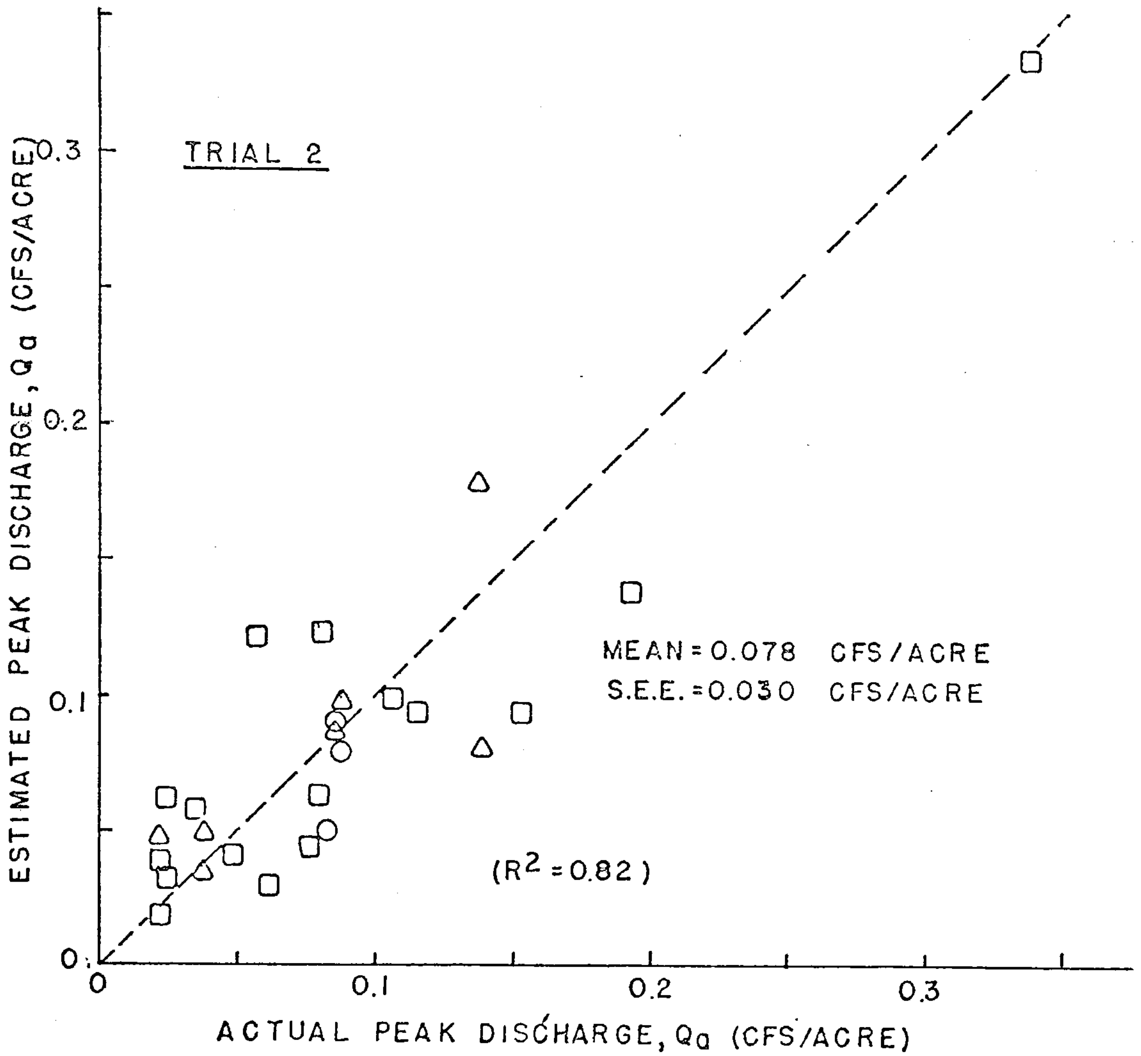

Fig. 4.9. Predicted (Equation 12) versus actual peak discharges, Walnut Gulch 1, 1955-1969

The equations for Q_a correlated with V_{20} and V_{10}, and for Q_a correlated with V_{20}, V_{10}, and ARI were

$$Q_a = 0.055 + 0.836V_{20} + 0.122V_{10}, \qquad (4.13)$$

and $$Q_a = 0.046 + 0.948V_{20} + 0.094V_{10} + 0.180(\text{ARI}) \qquad (4.14)$$

The estimated versus actual peak discharge for 5, as calculated from Equation 4.14 are shown in Figure 4.10. The maximum estimated and actual values were identical, 1.30 c.f.s./acre.

In Trial No. 2, ARI contributed significantly to the correlations for both watersheds which was extremely promising, since almost all the major flood peaks occurred when antecedent channel conditions were dry. The second largest event on 5 also had the largest ARI for the period of record, while for the first and third events, the ARI equaled zero.

With such a high correlation ($R^2 = 0.92$) and a relatively low standard error of estimate (about one-third of the mean), it was doubtful that the regression equation for 5 could be improved any further. The poorer correlation for 1 was probably because none of the runoff-producing storms covered the entire watershed and because most covered less than one-half of the watershed, and because of the much greater transmission losses. Also, the records for 1 were very poor in 1955 and only fair through 1963. From the available data, no significant difference could be defined in peak discharge from major storms occurring on different parts of the watershed. Other than rainfall variables, only antecedent channel conditions significantly affected rainfall-peak runoff correlations.

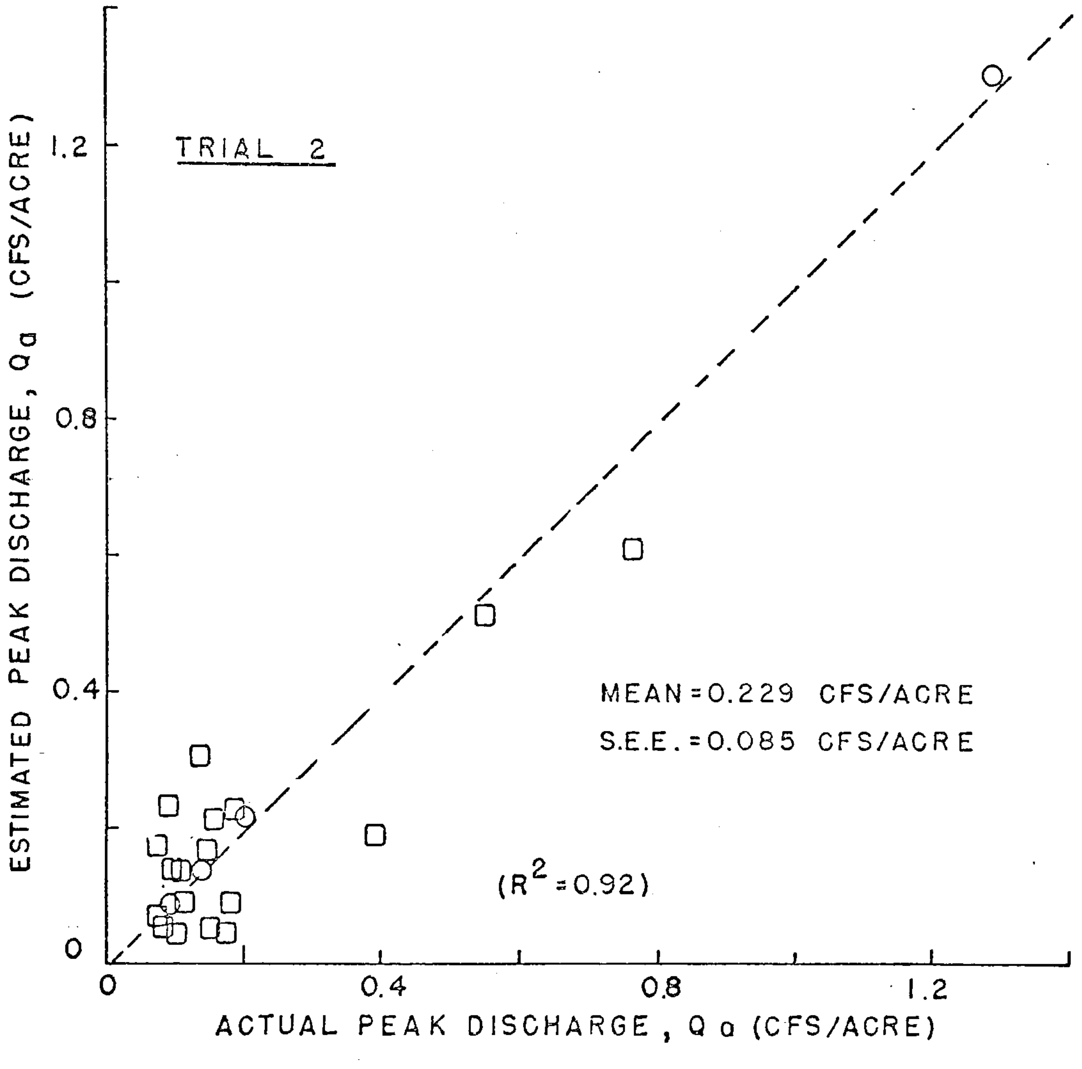

Fig. 4.10. Predicted (Equation 14) versus actual peak discharges, Walnut Gulch 5, 1955-1969

A realistic regression equation for predicting peak runoff might be

$$Q_a = k + aV_{05} + bV_{10} + cV_{15} + dV_{20} + eV_{25} + f(ARI) - gD_{edge}. \quad (4.15)$$

The analyses of the available data with the MLR program eliminated the variables that did not add significantly to the equation. Thus, V_{05}, V_{15}, and D_{edge} dropped out of the equation for 1 and 5; V_{10}, V_{20}, and V_{25} dropped out of the equations for 3; and only V_{15} was significant for 4. The equations which resulted for each of the four watersheds were reasonable. Logically, an increasing fraction of each level of rainfall should go to runoff.

Third Trial

Data for watersheds 3 and 4 were included in Trial No. 3. ARI values were calculated similarly to the method used for watershed 5. Rainfall volumes were calculated in square-mile inches, per 30 minutes, as was the case with 1 and 5.

Two equations for watershed 3 which were significant were

$$Q_a = 0.016 + 1.995V_{15} + 0.526V_{05} \quad (4.16)$$

and

$$Q_a = 0.149 + 1.843V_{15} + 0.475V_{05} - 0.205D_{edge}. \quad (4.17)$$

For Equation 4.16, R^2 was 0.79; for Equation 4.17, R^2 was 0.88. Adding D_{edge} to the variables V_{15} and V_{05} significantly improved the regression equation. As was the case in Trial No. 1, V_{15} was the best single variable, and adding V_{05} most improved the simple equation. As can be readily seen in Equations 4.16 and 4.17, the coefficients for

V_{15} and V_{05} do not indicate the percent of runoff from each volume of rainfall. This is true for all regression equations in this chapter.

Plots of predicted versus actual peak for Equations 4.16 and 4.17 show marked improvement for Equation 4.17 as opposed to Equation 4.16 (Figs. 4.11 and 4.12). The maximum peak was predicted with equal accuracy, but the scatter is much less for lower peaks for Equation 4.17 as would be expected because of the higher R^2.

The only significant input variable for watershed 4 in Trial No. 3 was again V_{15}. The resulting equation was

$$Q_a = 0.414 + 4.214V_{15} \qquad (4.18)$$

with R^2 equal to 0.80. Since 1.5 inches of rainfall in 30 minutes was recorded only once during the period of record, and since the one event so completely dominated the correlation between rainfall and peak runoff, a plot of the predicted and actual peaks was not very valuable. The equation was based on two points, the maximum peak discharge, and the average of all the other peaks (Fig. 4.13). The coefficient of 0.414 was about the average of the other 14 peaks. Because of the relatively poor record and the one dominant storm, no better equation, or correlation, would be expected from 4 with the available data.

Fourth Trial

The results from Trial No. 2 indicated that duration of runoff-producing rainfall might have a significant effect on the rainfall-peak runoff relationship. Therefore, the total times in which maximum 30-minute depths were recorded on the watershed were determined for 30 of

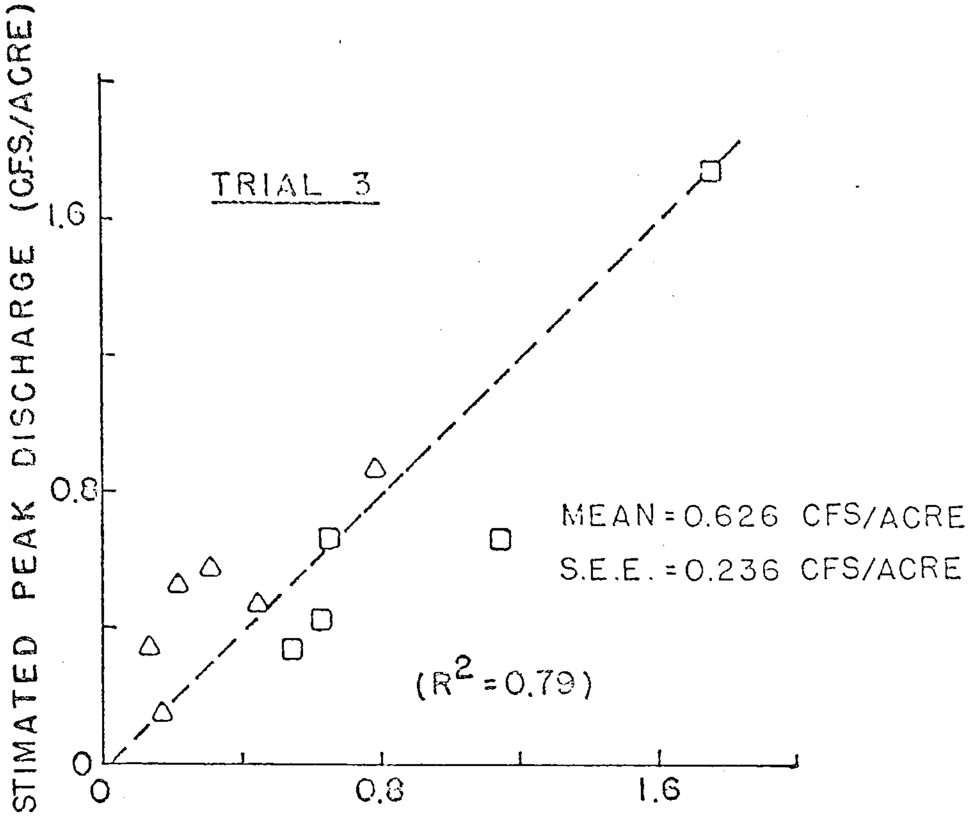

Fig. 4.11. Predicted (Equation 15) versus actual peak discharges, Walnut Gulch 3, 1955-1969

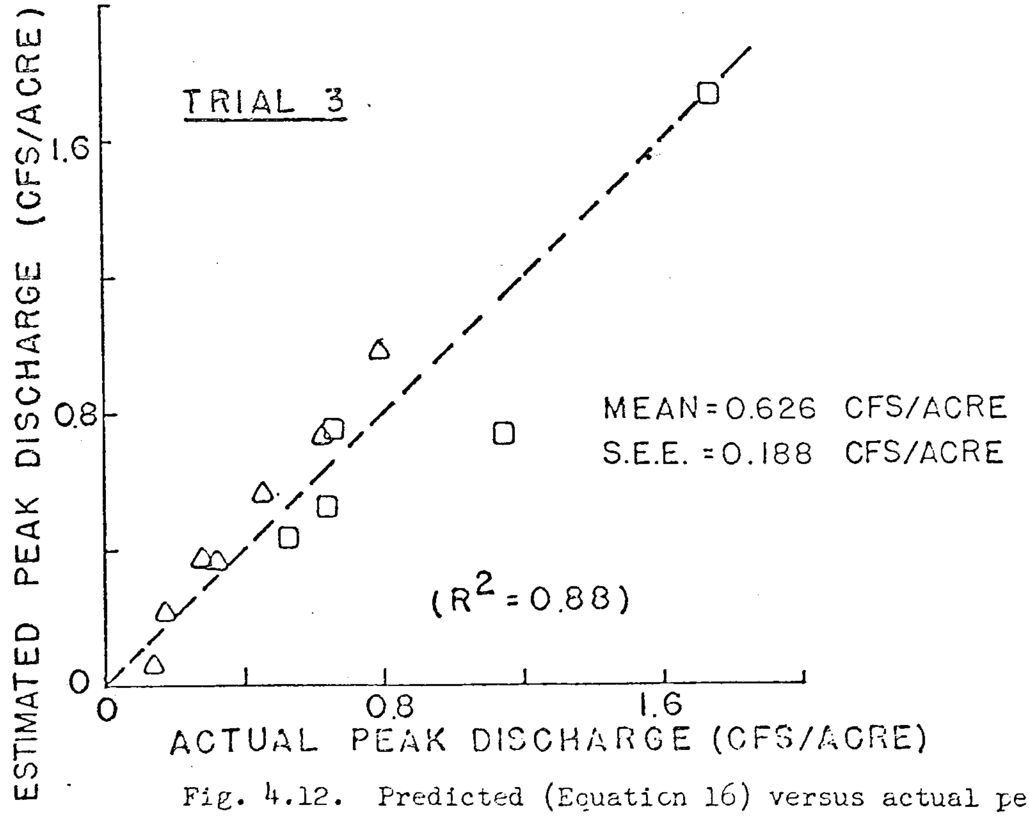

Fig. 4.12. Predicted (Equation 16) versus actual peak discharges, Walnut Gulch 3, 1955-1969

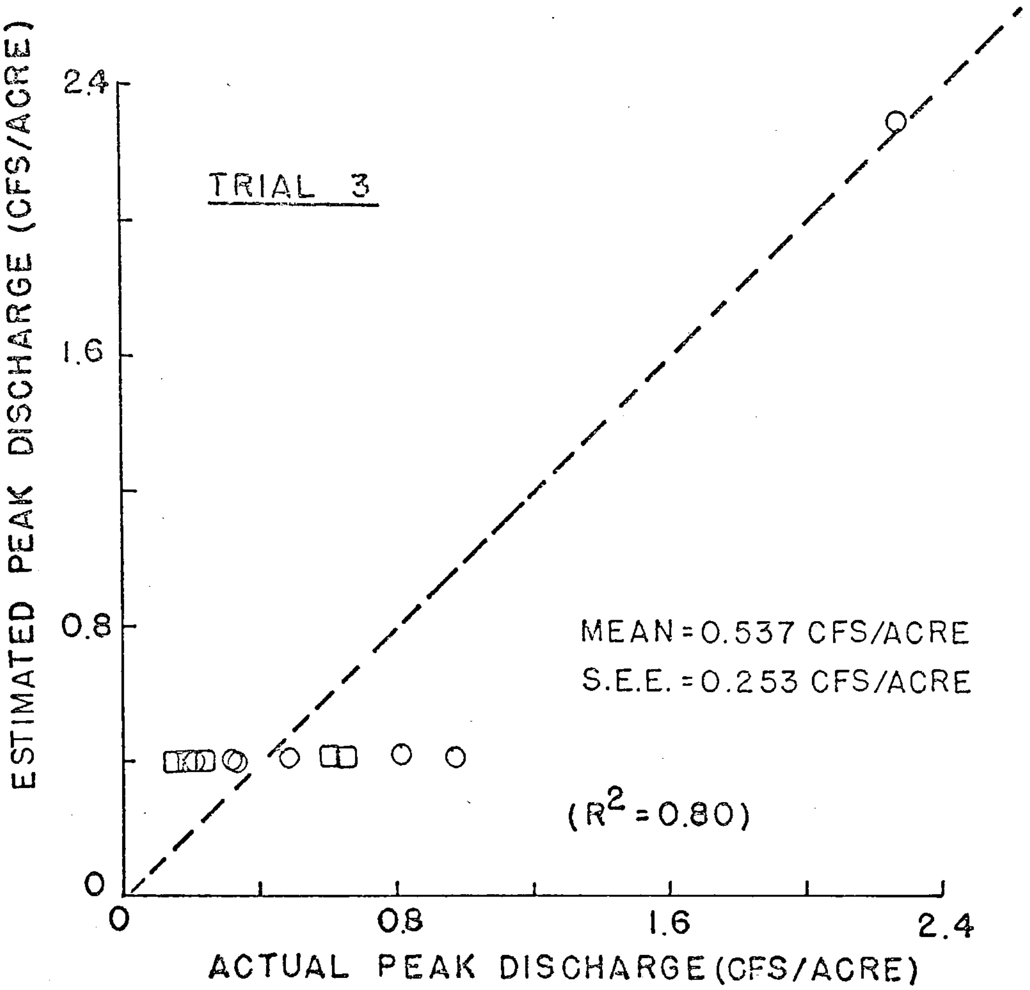

Fig. 4.13. Predicted (Equation 17) versus actual peak discharges, Walnut Gulch 4, 1955-1969

the 31 major peaks on 1. The storm on August 19, 1963 was deleted from the original 31 runoff events, since it was the only frontal-convective event of the 31. The values for storm duration, T, ranged from 30 minutes to 75 minutes. The average duration was 55 minutes.

Also, several minor errors were found in the original rainfall volumes and were corrected. These corrections were expected to change the coefficients and R^2 slightly, but not expected to change the rank of the variables.

The results from Trial No. 4 were inconclusive. There were no significant changes through the first three variables--V_{20}, V_{10}, and ARI in Equation 4.19, which was

$$Q_a = 0.016 + 0.01V_{10} + 0.104V_{20} + 0.008(ARI). \quad (4.19)$$

Because of the corrected data, R^2 was 0.81, as compared to 0.79 in Equation 4.11.

In Equation 4.20, storm duration, T, improved the R^2 to 0.84, which was not significant.

$$Q_a = 0.069 + 0.011V_{10} + 0.011V_{20} + 0.007(ARI) - 0.001T \quad (4.20)$$

However, since duration should be negatively correlated to peak discharge, the resulting equation was reasonable. If 30 were subtracted from each value of T, the constant would be reduced to 0.039, which would be more appropriate than 0.069.

Actually, neither ARI nor T can be used directly in a linear regression equation; although they may appear in the constant "k". Obviously, there must be rainfall before there can be runoff. The coefficients and values for ARI and T should give some indication of the role of antecedent channel conditions and storm duration on storm peaks as determined from a regression equation relating only rainfall volumes with peak runoff, but the form of the equation is not correct.

An equation of the following form which might apply for watersheds 1 and 5 could be

$$Q_a = (k + aV_{10} + bV_{15} + cV_{20} + dV_{25})(R)(C), \qquad (4.21)$$

which can be interpreted as a variation of the Rational Formula, $Q/A = Ci$. The coefficients correspond to the rational "C" and V_{10}, V_{15}, V_{20}, and V_{25} are intensities in volumes per 30 minutes. R is some measure of antecedent channel conditions, and C is some measure of storm duration. For dry antecedent conditions and average storm durations, R and C would equal one.

Fifth Trial

To best determine coefficients for rainfall values, V_{10}, V_{15}, V_{20}, and V_{25}, and the value of the constant R, only rainfall values for V_{10}, V_{15}, V_{20}, and V_{25} were used to develop a regression equation for watershed 1 in Trial No. 5. This regression equation was

$$Q_a = 0.035 + 0.009V_{10} + 0.040V_{20} + 0.142V_{25} \qquad (4.22)$$

which did not add much to previous knowledge. When V_{15} was added to the equation, the coefficient for V_{20} became negative, and the equation was no longer reasonable.

Sixth Trial

An equation similar to Equation 4.21 was developed from study of Equations 4.3, 4.11, 4.12, 4.19, 4.20, and 4.22. Several possible combinations of coefficients were assumed and the equations were checked by determining the peak discharges and plotting them against the actual peak discharges. After several trials, three equations were developed for watershed 1 that appeared to give good results (Figs. 4.14-4.16). These equations were

$$Q_a = (0.02 + 0.01V_{10} + 0.01V_{15} + 0.03V_{20} + 0.14V_{25})(R), \qquad (4.23)$$

$$Q_a = (0.02 + 0.01V_{10} + 0.01V_{15} + 0.03V_{20} + 0.15V_{25})(R)(C), \qquad (4.24)$$

and

$$Q_a = (0.015 + 0.01V_{10} + 0.01V_{15} + 0.03V_{20} + 0.17V_{25})(R)(C) \qquad (4.25)$$

The results were plotted against the actual peak discharges, and then compared with the results from Equation 4.19. Also, the results were compared statistically by least squares correlation to see which equation gave the best fit to the data. For Equations 4.23, 4.24, and 4.25, R^2 was 0.820, 0.844, and 0.837, respectively.

Although values from Equation 4.24 gave the highest R^2, there was no statistically significant difference in the equations. However, with more and better data, R and C might become more important, so Equation 4.24 was chosen since it was as good as could be developed at this time. Also, R^2 for Equations 4.20 through 4.25 was essentially the same, which seemed to be as good a correlation as one could expect from the available data.

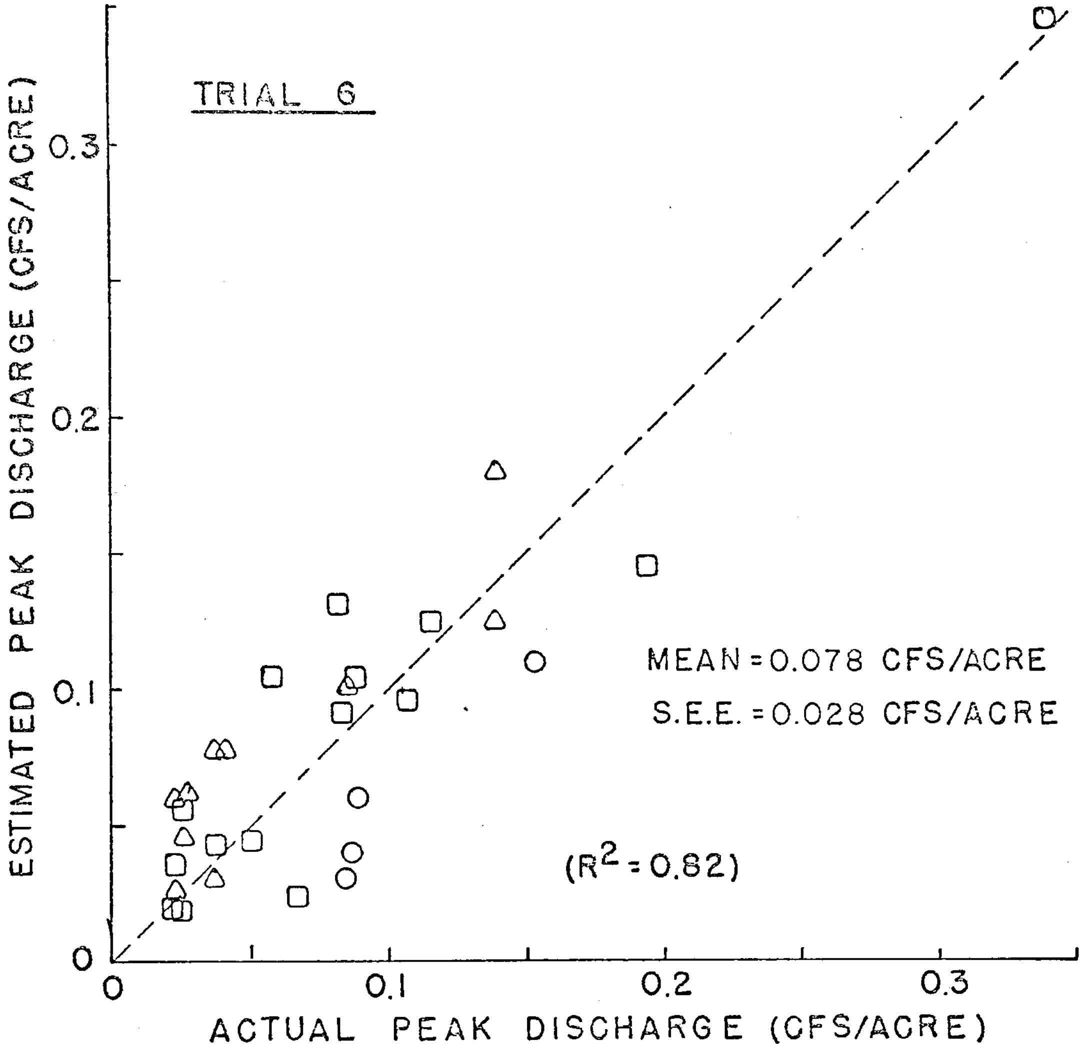

Fig. 4.14. Predicted (Equation 23) versus actual peak discharges, Walnut Gulch 1, 1955-1969

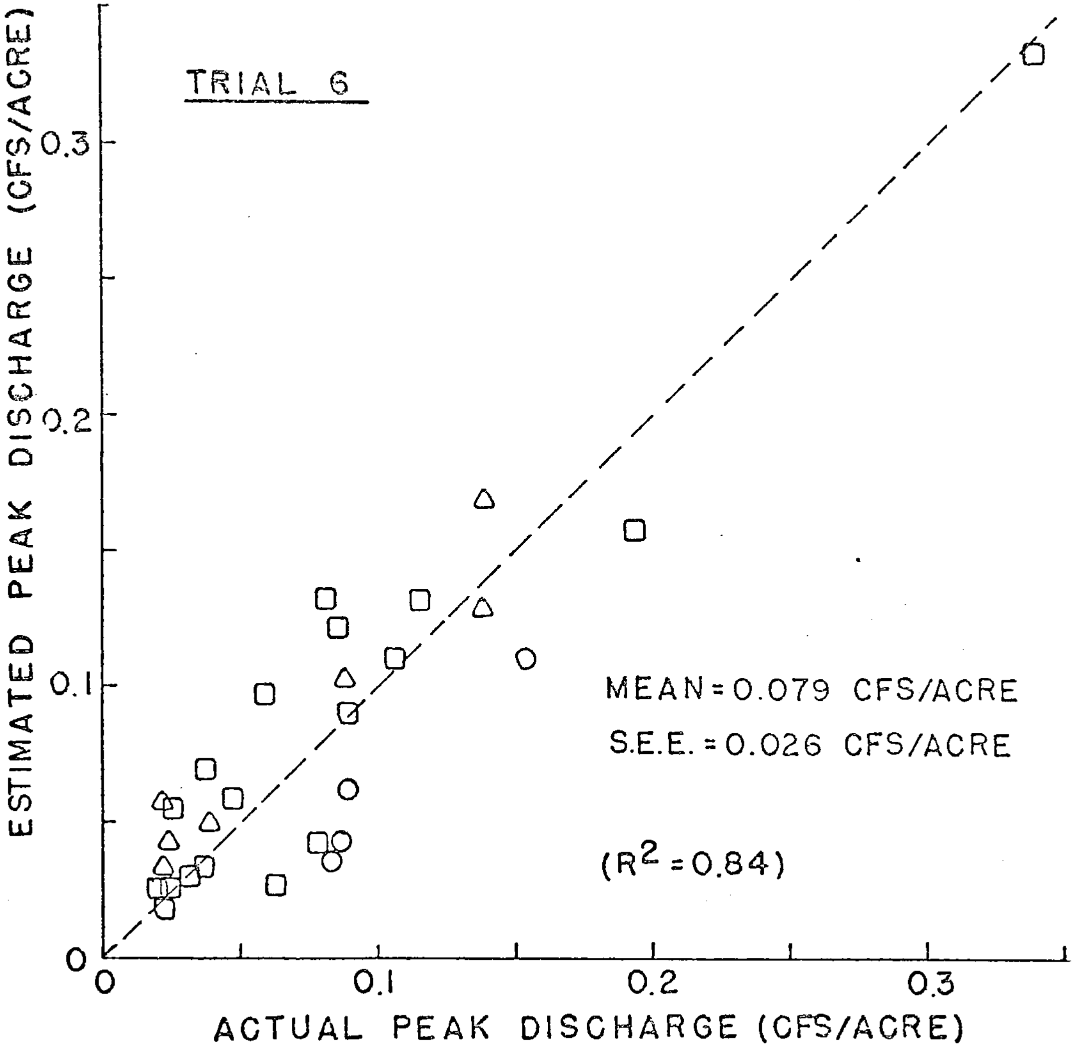

Fig. 4.15. Predicted (Equation 24) versus actual peak discharges, Walnut Gulch 1, 1955-1969

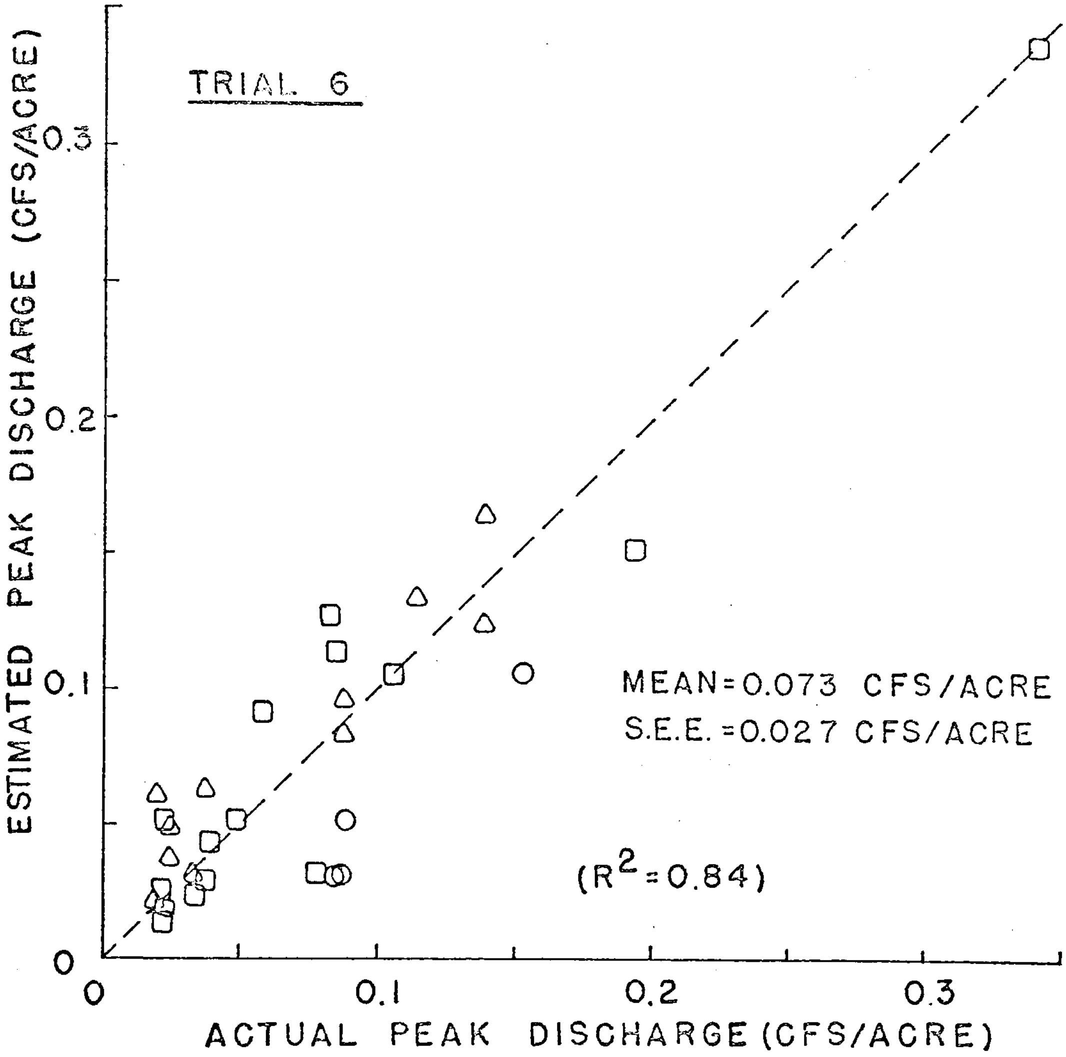

Fig. 4.16. Predicted (Equation 25) versus actual peak discharges, Walnut Gulch 1, 1955-1969

Seventh Trial

In Trial 7, equations for peak runoff from watershed 5 were investigated similarly to Trial Nos. 5 and 6 for watershed 1. First, only the rainfall volumes for V_{10}, V_{15}, and V_{20} were used to develop a regression equation for peak runoff. Second, an equation was developed from available information which best described the rainfall-peak runoff relationship.

An equation was developed by trial and error from past information, particularly from Equation 4.9. The final form of this equation was

$$Q_a = (0.05 + 0.1V_{10} + 0.15V_{15} + 0.40V_{20})(R) + 0.60V_{25} . \qquad (4.26)$$

The coefficients for Equation 4.26 were much larger than those for Equation 4.24 because of lesser channel abstractions on the smaller watershed. Antecedent channel conditions for smaller watersheds such as 5 probably affect the smaller volumes of channel runoff more than the larger volumes. Rainfall volumes of more than 2.5 inches in 30 minutes were assumed to be unaffected by antecedent channel conditions. A plot of the predicted peaks from this equation versus the actual peaks indicated a very good fit of the data (Fig. 4.17). The peak values from Equation 4.26 were also compared to the actual values by least squares, and the R^2 was 0.925.

The extremely good correlation was due to two factors. First, the best fit for the equation depended essentially on fitting 4 points--the three highest peaks and the average of all other peaks (Fig. 4.17). Second, since antecedent conditions were dry for the first and third

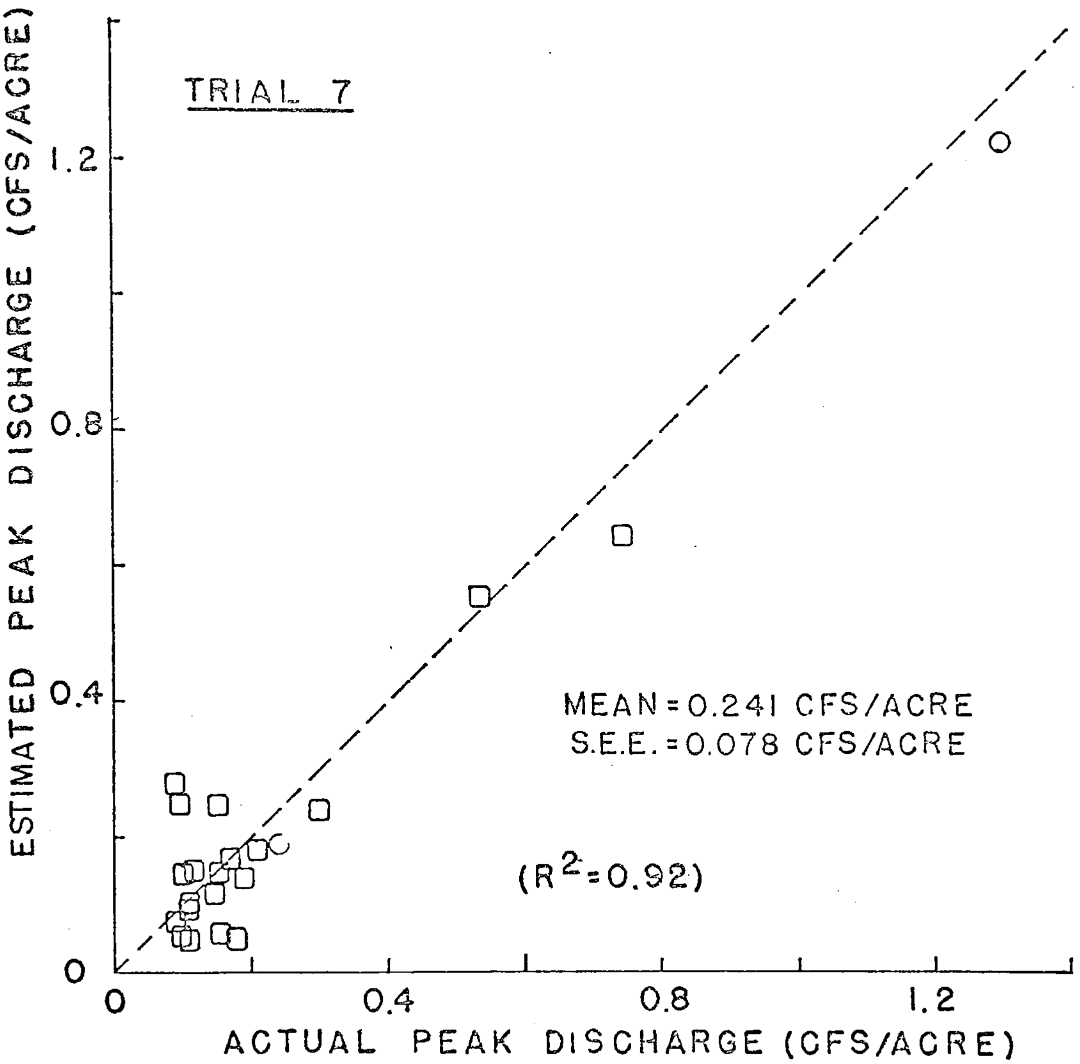

Fig. 4.17. Predicted (Equation 26) versus actual peak discharges, Walnut Gulch 5, 1955-1969

highest peaks, and relatively wet for the second; and the low peaks didn't make any difference, the ARI factor, R, increased the magnitude of the second peak, which improved R^2.

Observations on Regression Equations

The MLR program is not sensitive to realities, but simply picks the variable that best explains the variation in the dependent variable and then adds variables that best improve this primary relationship. However, the program will not go back and determine whether, for example, the second and fourth variables in combination might be better than the first and second variables. The form of the equation must be assumed. However, as indicated earlier, the MLR program is extremely helpful in indicating which of many variables are most likely to have a significant effect on the overall rainfall-runoff relationship.

Reasonable equations were developed to predict peak runoff from rainfall for watersheds 1 and 5. The equations were based on the effective drainage areas--33,800 acres for 1 and 4,100 acres for 5. These equations could be used to predict higher peaks within certain degrees of accuracy. For 1, the highest peak on record was 11,500 c.f.s.; for 5, the maximum peak of record was about 5,300 c.f.s. Approximate equations might be developed for similar watersheds other than watersheds 1 and 5 by estimating coefficients from differences in watershed size.

From Equations 4.24 and 4.26 and available data on channel abstractions approximate rainfall-peak discharge equations (4.27 and 4.28) were estimated for watersheds 2 and 6. All four equations were listed for comparison according to watershed size starting with watershed 1 (58 square miles), watershed 2 (43 square miles), watershed 6 (37 square miles), and watershed 5 (8 square miles), respectively. The equations were

$$Q_a = (0.02 + 0.01V_{10} + 0.01V_{15} + 0.03V_{20} + 0.15V_{25})(R)(C) \qquad (4.24)$$

$$Q_a = (0.02 + 0.012V_{10} + 0.015V_{15} + 0.04V_{20} + 0.20V_{25})(R)(C) \qquad (4.27)$$

$$Q_a = (0.03 + 0.015V_{10} + 0.02V_{15} + 0.05V_{20} + 0.25V_{25})(R)(C) \qquad (4.28)$$

$$Q_a = (0.05 + 0.10V_{10} + 0.15V_{15} + 0.40V_{20})(R) + 0.60V_{25} \qquad (4.26)$$

Increasing coefficients for decreasing watershed size were almost entirely because of lesser channel abstractions with decreasing watershed size. The equations and available data suggest that there are much greater differences in rainfall-runoff characteristics between the 8.0-square-mile and 37-square-mile watersheds than between the 37-square-mile and the 58-square-mile watersheds. Unfortunately, only very short records are available on Walnut Gulch for watersheds between 8.0 and 37 square miles.

CHAPTER 5

THUNDERSTORM RAINFALL MODELS

Runoff in southeastern Arizona results almost entirely from summer thunderstorm rainfall. Therefore, mathematical descriptions or models of thunderstorm rainfall are particularly important to researchers and others involved in hydrologic investigations in the Southwest.

Atterbury Models

Of particular interest in developing rainfall models for southeastern Arizona are models developed by Woolhiser and Schwalen (1959) and Fogel and Duckstein (1969). These models were developed from thunderstorm rainfall on the 18-square-mile Atterbury watershed near Tucson, Arizona. Although there are significant climatological and topographical differences between the Walnut Gulch and Tucson areas, considerable similarity would be expected in the areal extents and magnitudes of thunderstorm rainfall at both stations.

Both the Woolhiser-Schwalen and Fogel-Duckstein models were smooth-domed. That is, the representation rainfall by depth-area was almost constant near the storm center. The Woolhiser-Schwalen model dropped to zero rainfall rather rapidly with increasing distance from the center, while the Fogel-Duckstein model dropped and then became asymptotic to the surface with zero rain at infinity.

The Woolhiser-Schwalen model was based on 18 storms in a three-year period with a maximum recorded center depth of 2.5 inches. The regression equation was

$$\log Y = 1.57 \log X + 1.08, \qquad (5.1)$$

where Y = isohyetal area in square miles

and X = storm center depth minus the isohyetal depth in inches.

The Fogel-Duckstein model was based on 12 years of record with 2 storms with maximum recorded center depths of 2.5 inches. The area-depth formula was

$$R = R_o e^{-r^2 b} \qquad (5.2)$$

where $b = 0.27e^{-0.67R_o}$

R_o = storm center depth

R = depth of rainfall along an isohyet which is at a distance r from the center.

The two models were very similar (Fig. 5.1), as would be expected, since they were based on data from the same watershed. The two models differ considerably for low values because of the mathematical method of fitting the data, but are essentially equal in the ranges of runoff-producing rainfall. Both models refer to rainfall volume from individual thunderstorms, but do not suggest a design duration for these thunderstorm rainfalls.

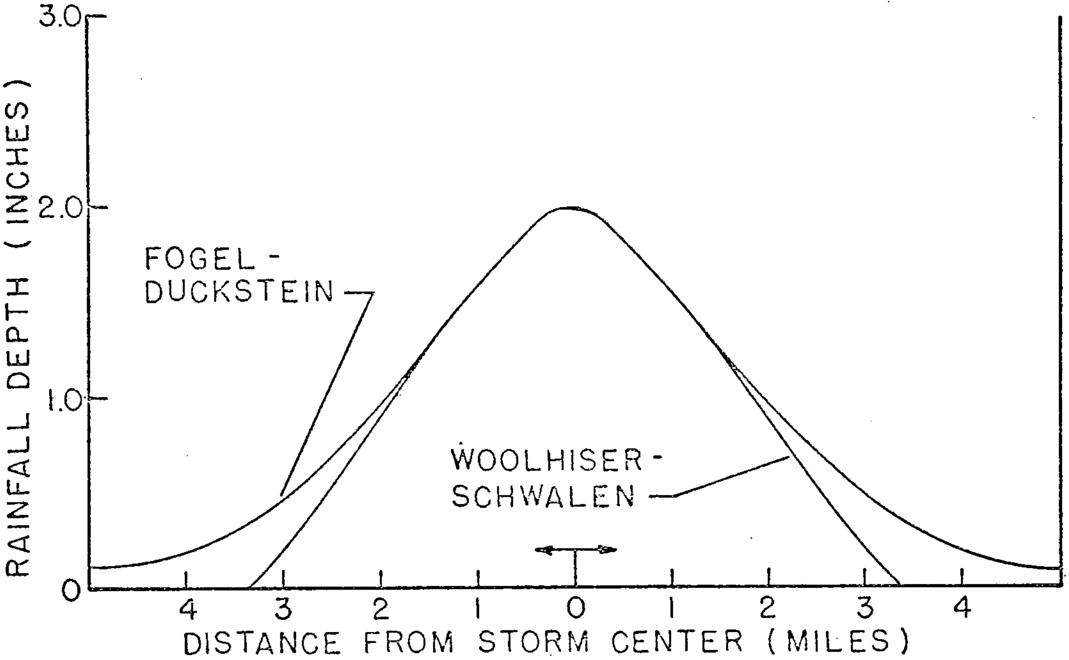

Fig. 5.1. Comparison of Woolhiser-Schwalen and Fogel-Duckstein models for a 2-inch storm

Walnut Gulch Model

Total Storm Rainfall

Osborn (1970) stated that depth-area relationships for storms on Walnut Gulch are important for runoff analysis from thunderstorm rainfall. Also, the shape of the rainfall pattern and the total area covered by runoff-producing rainfall are important in determining rainfall-runoff relationships and runoff frequencies, particularly if the runoff record is relatively short.

From 1961 through 1968, good rainfall records were available from an 80-gage-network on the Walnut Gulch watershed. From these records, isohyetal maps were plotted for all the runoff-producing storms. These, basically, were storms in which more than 0.6 inch of rainfall was recorded at some point or points on the watershed and point intensities of at least 0.5 inch per hour were recorded some time during the storm. In this period, 1961 through 1968, there were about 50 storms of over 1 inch of rainfall, and these storms were used in the initial development of models of the total storm rainfall on Walnut Gulch.

From these 50 storms, about 45 storm centers were well enough defined to include in the analysis. However, no storm in which more than 1.2 inches of rainfall was recorded at some point on the watershed was completely defined within the watershed. In other words, the storms overlapped the rain gage network for depths of greater than 0.8 inch. However, for about 45 of them enough rainfall fell on the watershed to make determinations of shape versus depth.

In a significant number of the storms no rainfall was recorded on at least some part of the watershed. Court (1961) believed that, for a logical rainfall model, as one moves away from the center of the storm, an asymptotic type of model develops, and there is some rainfall to an almost infinite distance. This appears to be incorrect for purely convective storms. There were enough storms on the watershed that did not record rainfall at some points to determine that whatever model was used, it theoretically should not be asymptotic to the zero surface.

Storm rainfall on Walnut Gulch appeared to be more elliptical than circular in form. In general, one side or edge of the storm, as represented by isohyetal mapping, was much steeper than another side. This steep side was represented by tightly spaced isohyets and is referred to in this paper as the short radius of the storm. The widely spaced isohyets are referred to as the long radius. Although the long and short radii of the rainfall were not generally at right angles, they were enough so that the storms did appear to be more elliptical than any other simple shape.

Distances were measured from the storm center to each decreasing isohyet. By far the greatest rainfall, in both maximum recorded depth and volume was recorded on the afternoon of September 10, 1967. About 3.45 inches of rain was recorded at the storm center. The next three largest storms produced 2.65 inches, 2.62 inches, and 2.53 inches of rainfall at their centers. In Figure 5.2, the long and short radii for the four largest storms are compared. The next two figures represent the September 10 storm as opposed to average storms in lower ranges of rainfall, 2.21 inches to 2.40 inches; 2.01 inches to

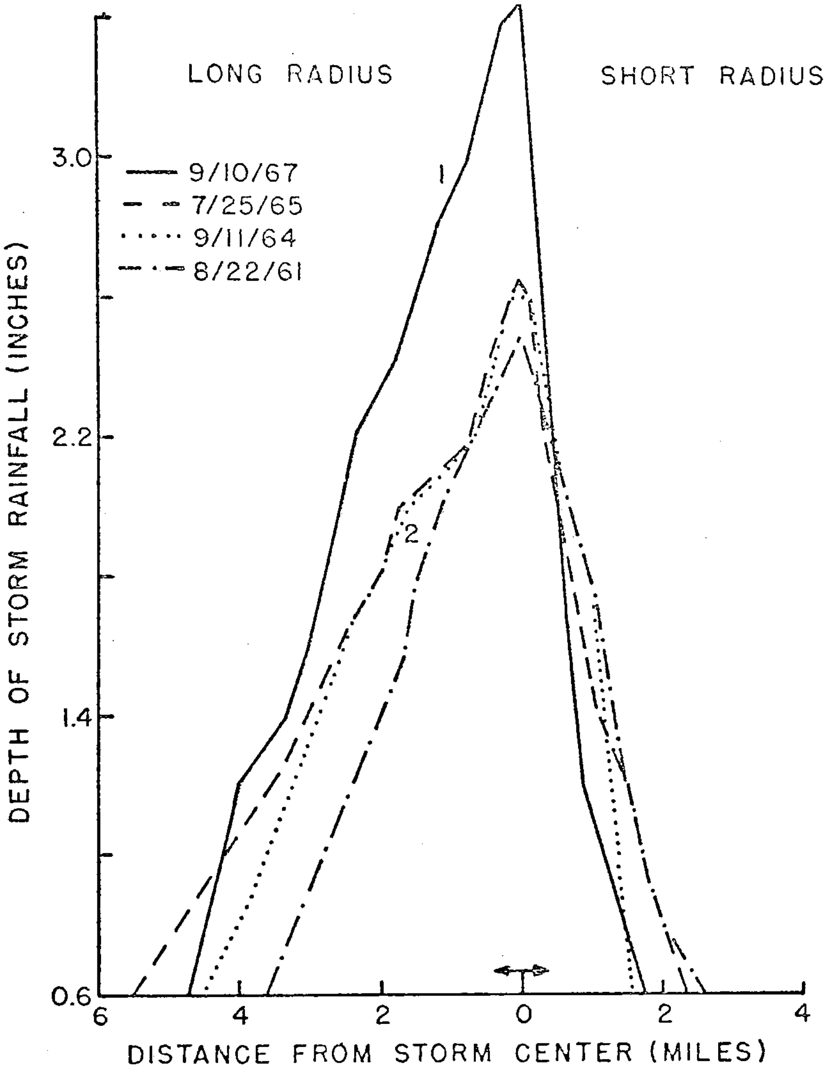

Fig. 5.2. Schematic representation of 4 extreme rainstorms based on distance from storm center to given isohyets, Walnut Gulch, 1961-1968

2.20 inches; and 1.81 inches to 2.00 inches and to average storms in the ranges from 1.41 inches to 1.60 inches; 1.21 inches to 1.40 inches; and 1.01 inches to 1.20 inches (Figs. 5.3 and 5.4).

From these figures, it appeared that the largest storm, September 10, 1967, did not cover significantly more area at the 0.6 inch isohyet than did the next three largest storms. This was particularly true on the short radius where the larger storms appeared to pile rainfall volumes one upon another and the isohyets in these storms became more and more closely packed as the depth increased. On the other hand, as indicated by the next two figures, as the storms decreased in maximum depth, they also appeared to decrease in the length of their longer radius.

Composite storms were developed from these three figures (Fig. 5.5). The composites were: (1) the largest event; (2) an average of the three next largest storms; (3) an average of the 14 storms between 1.61 and 2.40 inches; (4) an average of the 13 storms between 1.41 and 1.60 inches; and (5) an average of the 14 storms between 1.01 and 1.40 inches. The composite storms were made as representative as possible by taking the same size sample for each of the lower 3 storms, by averaging the 3 larger events that were "grouped" together, and taking the maximum event as it was. Straight line extrapolations of the composite storms in Fig. 5.6 from 0.6 to zero inch strongly suggest that thunderstorm rainfall covered about the same area for all events in which center rainfalls of more than 1.0 inch were recorded. For less than 1 inch, thunderstorm rainfall covered less area. It might be

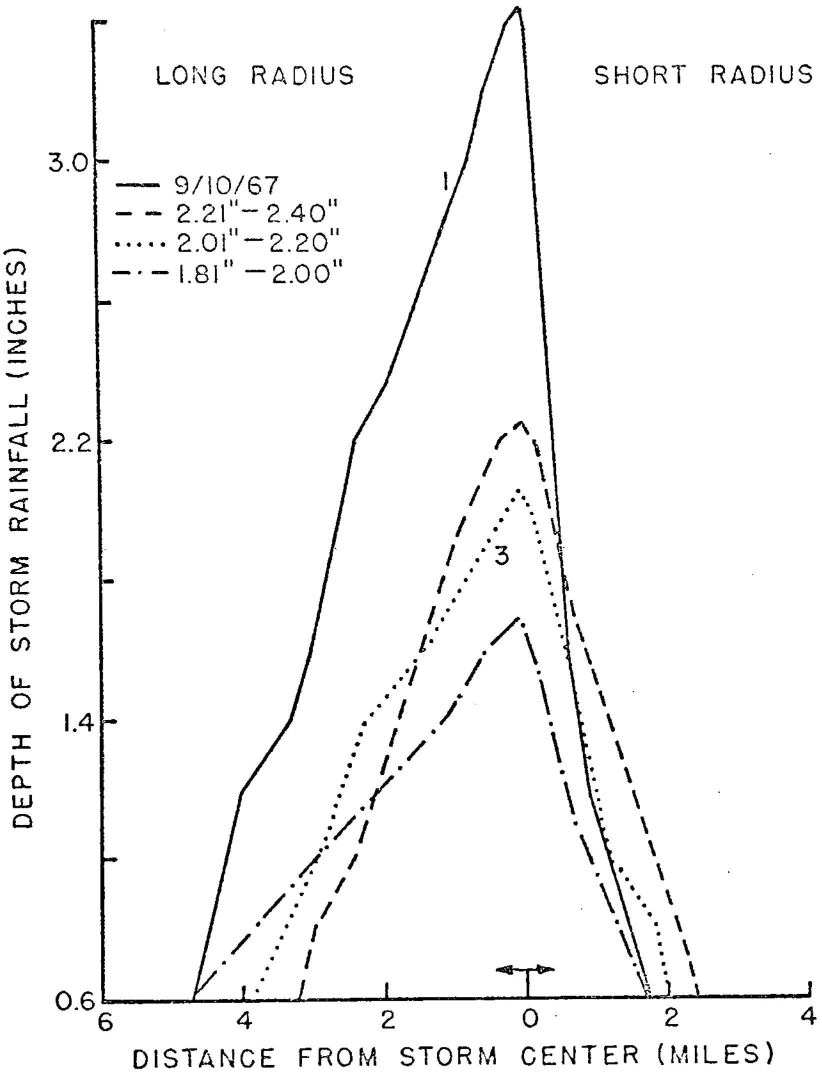

Fig. 5.3. Schematic representation of the maximum rainstorm and 3 averaged events based on distance from storm center to given isohyets, Walnut Gulch, 1961-1968

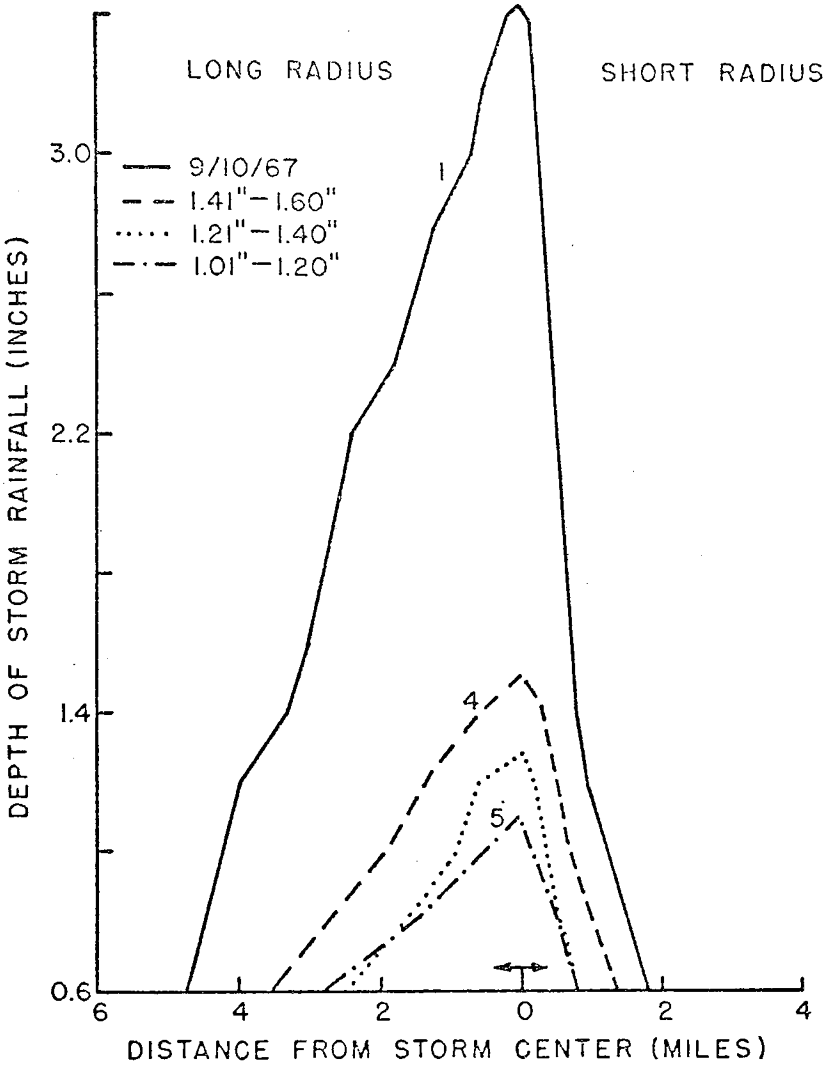

Fig. 5.4. Schematic representation of the maximum rainstorm and 3 averaged events based on distance from storm center to given isohyets, Walnut Gulch, 1961-1968

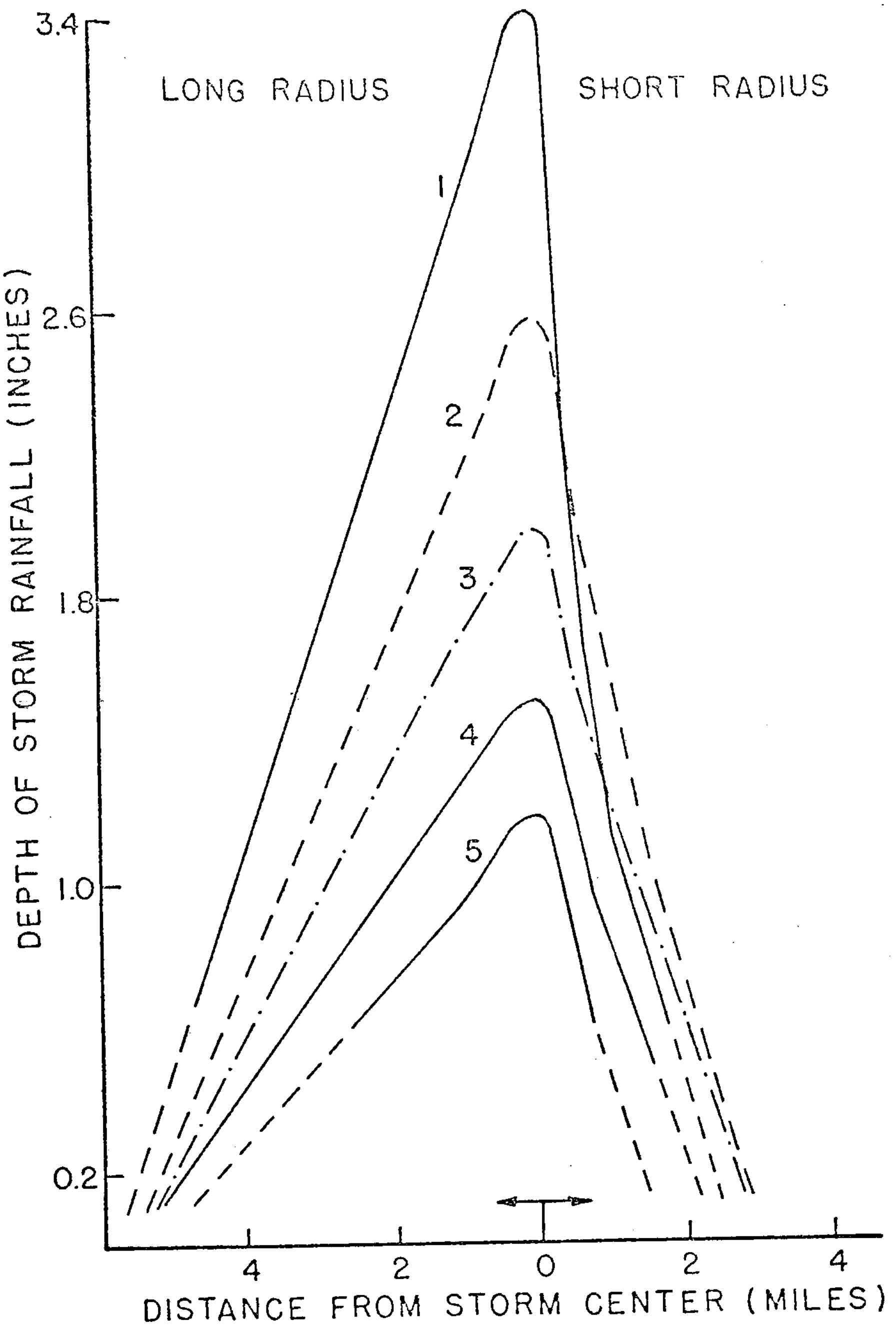

Fig. 5.5. Composite storms from schematic representations from Figures 5.3-5.5, Walnut Gulch, 1961-1968

noted, on the other hand, that frontal storms, which generally produce less than one inch of rainfall, cover much larger areas.

Woolhiser and Schwalen (1959) assumed a circular pattern or a true bell-shaped volume of rainfall for their models. Fogel (1968) suggested that rainfall from individual thunderstorms appeared to be elliptical, but that the 1-1/2 to 1 ratio of long to short axis was small enough to assume circular models. Therefore, Fogel and Duckstein assumed a circular pattern for their model. On Walnut Gulch, the pattern appeared to be more elliptical with ratios of 2 or 3 to 1. When the 2-inch-storms for each of the three models were compared, the volumes of rainfall were almost the same above 0.6 inch (Fig. 5.6). This indicated, or at least suggested, that both models were in the right order of magnitude in representing thunderstorm rainfall. The four Walnut Gulch models for different depths of rainfall were plotted as partial isohyet maps assuming elliptical shapes (Fig. 5.7). The Woolhiser-Schwalen model appeared to represent an average of the short and long radius of the Walnut Gulch figures (Fig. 5.8).

The shape, orientation, and areal extent of thunderstorm rainfall are important in determining the relative frequency with which such storms could occur on a watershed of given size and shape. However, one must decide whether runoff is better correlated to some other shorter duration within the storm than to total storm rainfall before further development of rainfall-runoff relationships. In this respect, the best duration to use may vary with watershed size. Shorter durations of rainfall might be expected to be best correlated with runoff on very small watersheds, with the duration increasing with watershed size.

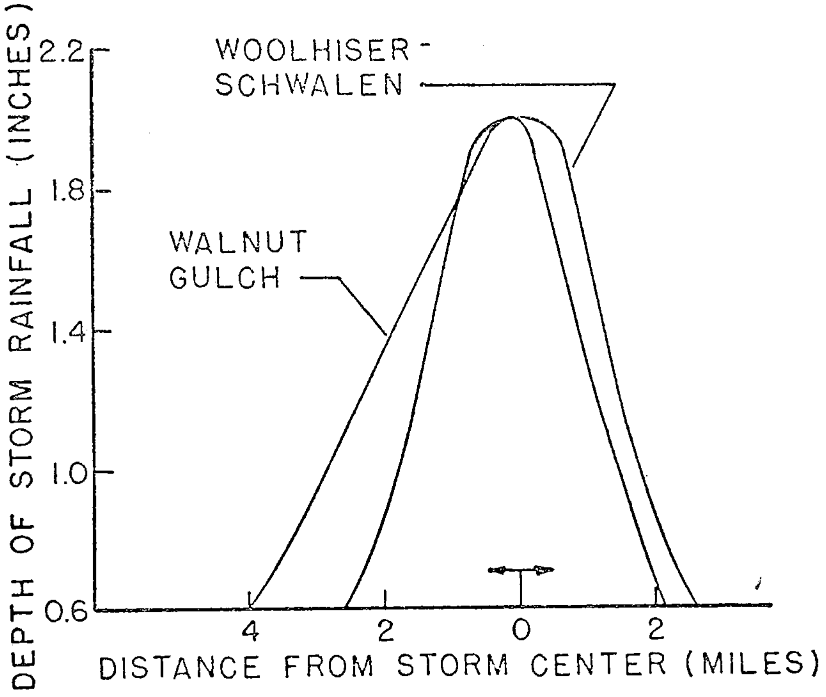

Fig. 5.6. Comparison of Woolhiser-Schwalen and Walnut Gulch models for a 2-inch storm

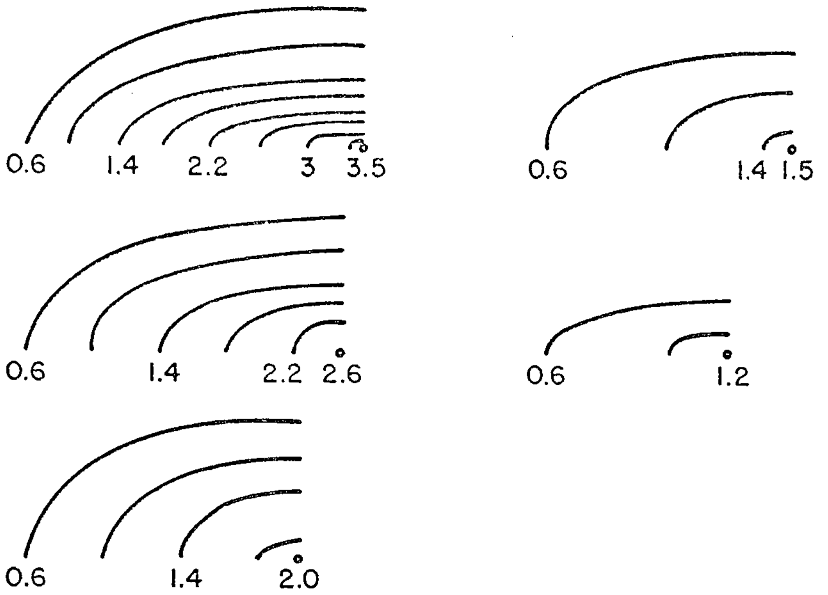

Fig. 5.7. Partial isohyetal maps of composite storms (from Figure 5.5), Walnut Gulch

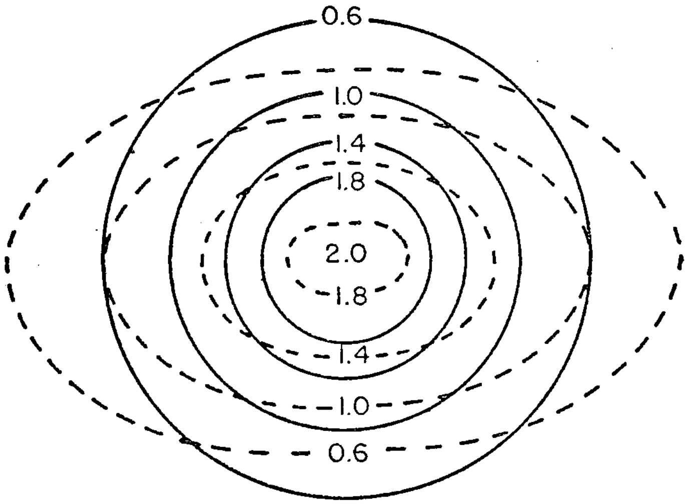

Fig. 5.8. Isohyetal comparison of Woolhiser-Schwalen and Walnut Gulch models for center depth of 2 inches

Maximum 30-Minute-Rainfall

All storms on Walnut Gulch in which more than 2.0 inches of rain fell in 30 minutes were investigated in developing a model for runoff-producing rainfall. Only storms that appeared to be centered within the Walnut Gulch watershed boundaries were used. There were five storms in this category--August 17, 1957; August 14, 1958; August 22, 1961; July 22, 1964; and September 10, 1967 (Figs. 5.9-5.13). Only one other storm during the period of record (July 26, 1959) exceeded 2 inches of rainfall in 30 minutes. This storm appeared to be centered on or just south of the watershed boundary. The five storms described here produced five of the eight largest peak discharges of record from Walnut Gulch. The peaks ranked as 1, 4, 5, 6, and 8 for the record 1957, 1958, 1964, 1967, and 1961 storms, respectively (Table 5.1).

Table 5.1. Rainfall area for five major events on Walnut Gulch watershed

Date	Peak R.O. rank	Area of rainfall for given isohyets (sq. mi.)					Maximum 30-min. depth of rainfall (inches)
		0.5	1.0	1.5	2.0	2.5	
8-17-57	1	32	18	7	4	2	2.63
8-14-58	8	25	10	4	1		2.35
8-22-61	6	18	10	6	1		2.27
7-22-64	4	30	14	4	1		2.06
9-10-67	5	31	17	9	1.5	0.5	2.52

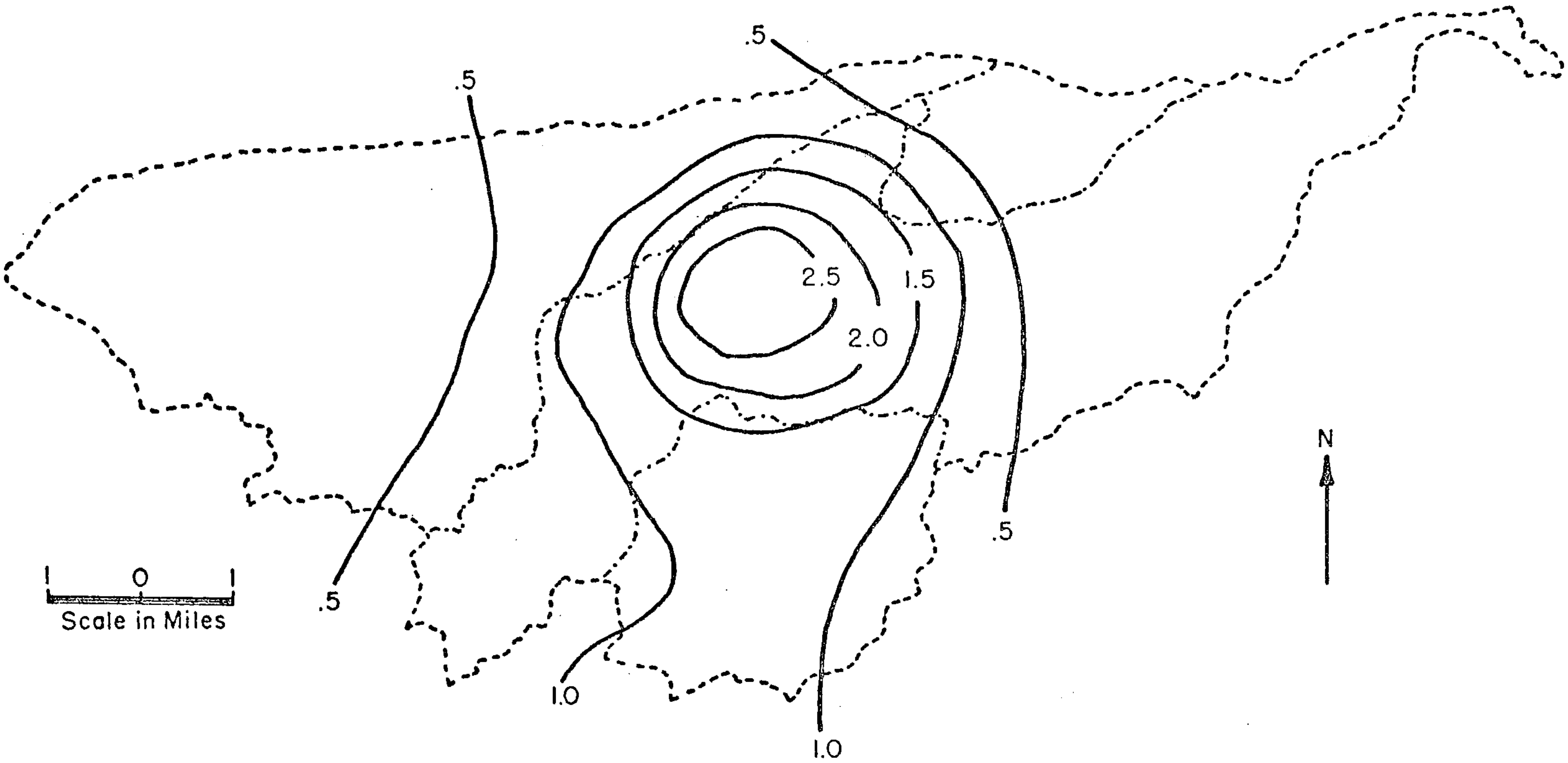

Fig. 5.9. Isohyetal map of maximum 30-minute rainfall, August 17, 1957, Walnut Gulch

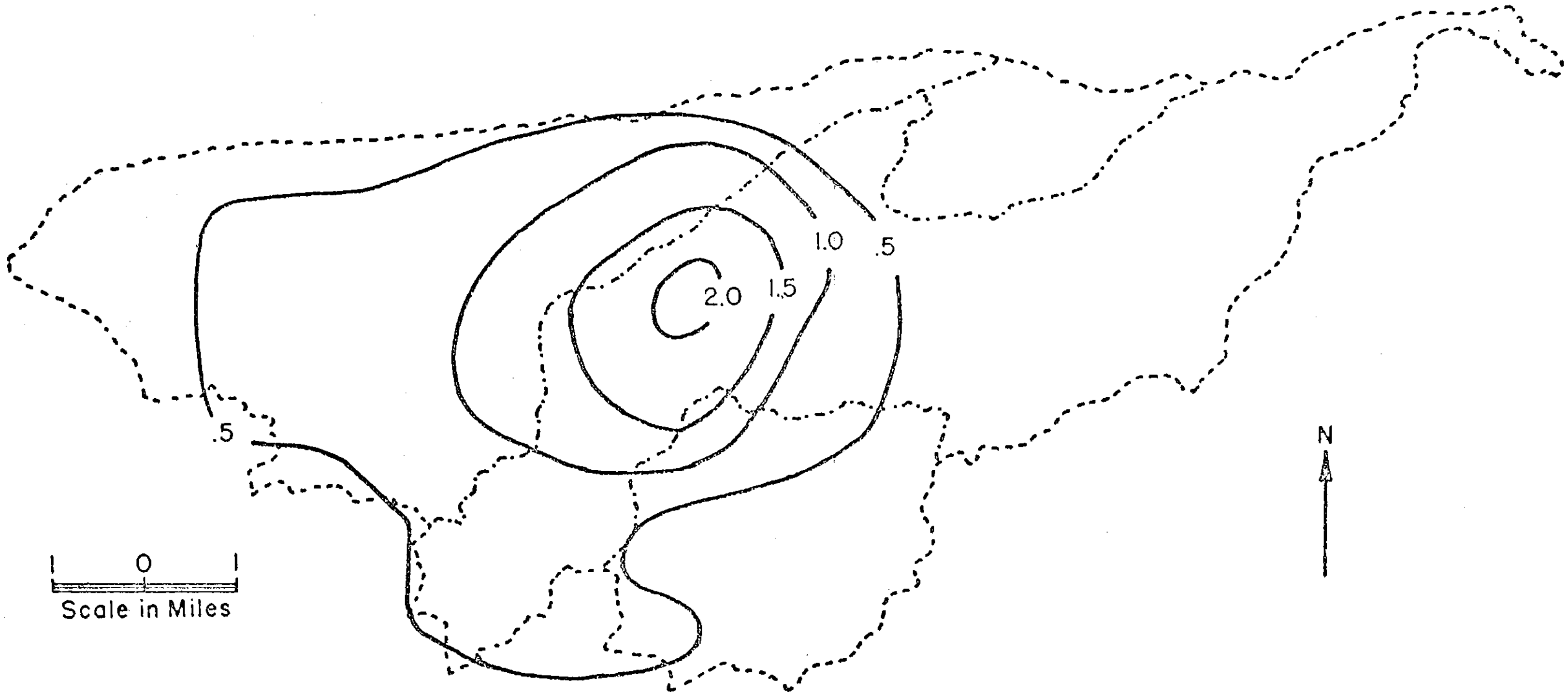

Fig. 5.10. Isohyetal map of maximum 30-minute rainfall, August 14, 1958, Walnut Gulch

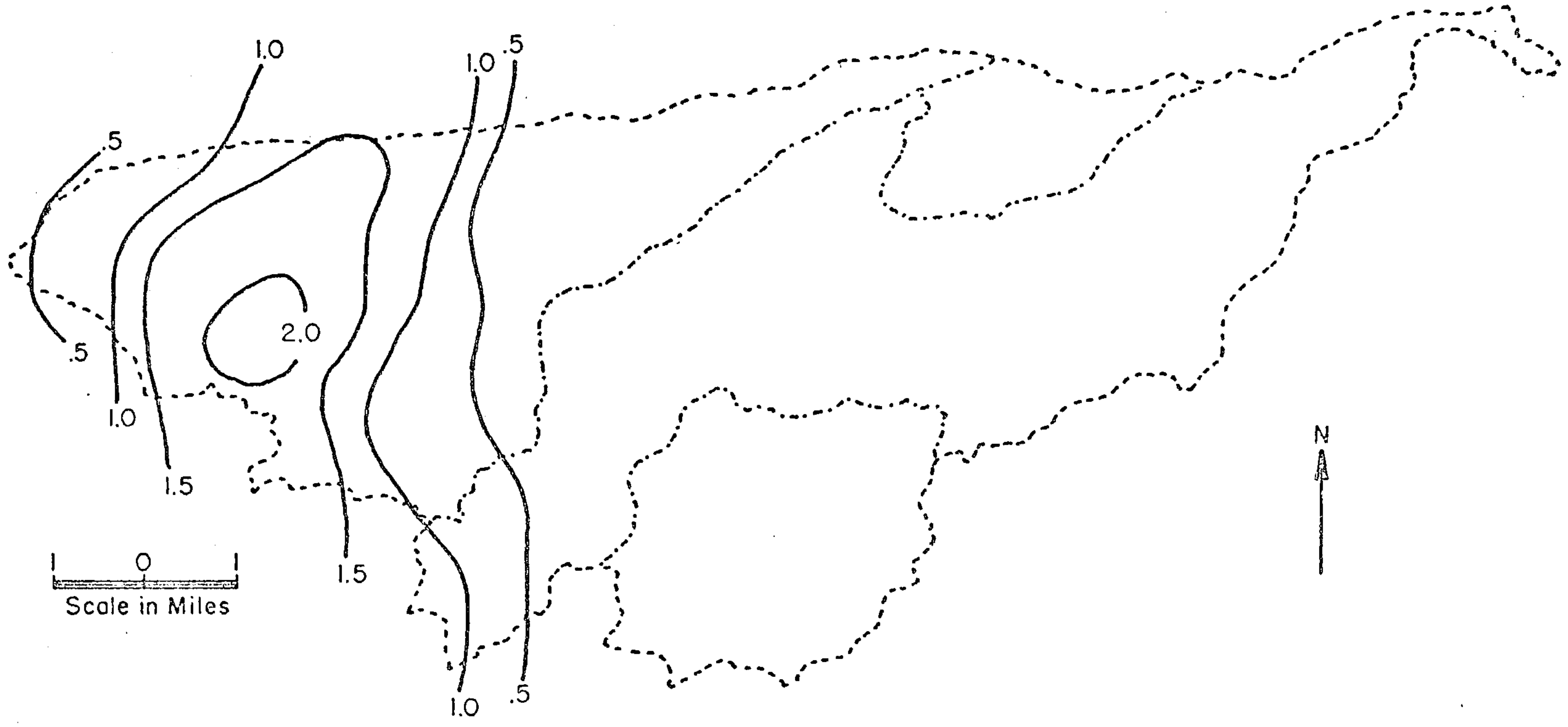

Fig. 5.11. Isohyetal map of maximum 30-minute rainfall, August 22, 1961, Walnut Gulch

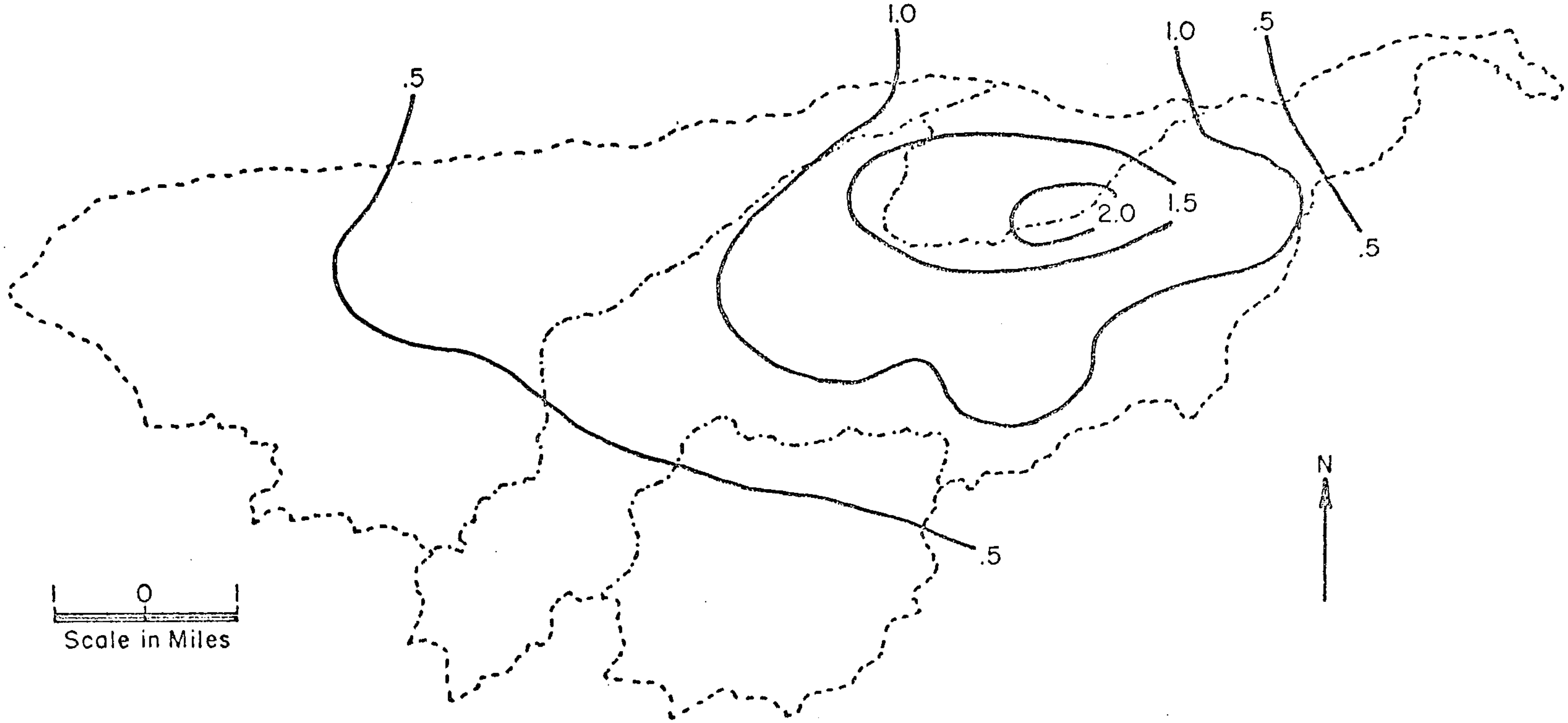

Fig. 5.12. Isohyetal map of maximum 30-minute rainfall, July 22, 1964, Walnut Gulch

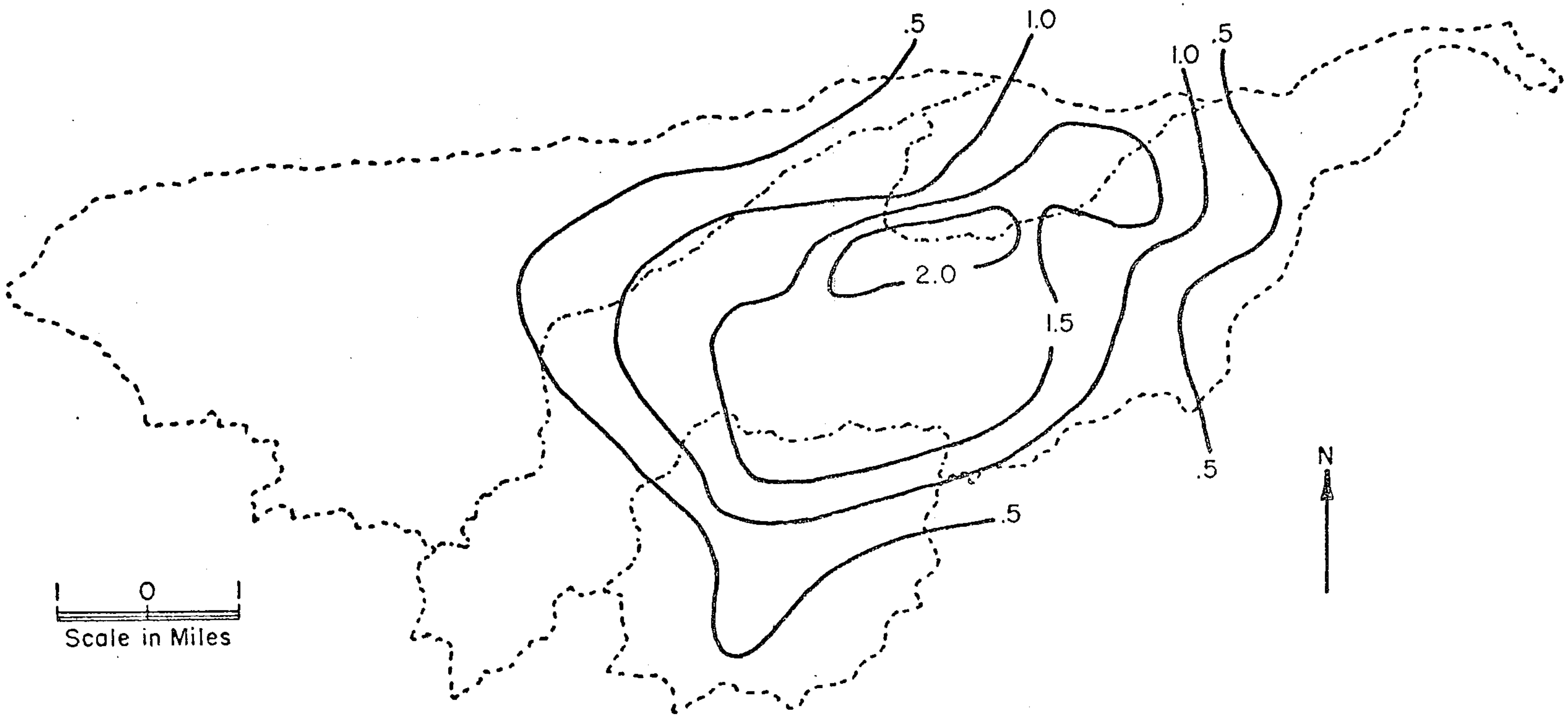

Fig. 5.13. Isohyetal map of maximum 30-minute rainfall, September 10, 1967, Walnut Gulch

Four of the largest 15 peaks, including the third largest, occurred in July 1955, but because of poor runoff records and inadequate rainfall data, they were excluded in the development of the conceptual model. The second largest peak discharge (August 2, 1957) was produced from rain concentrated on and around the lower end of the watershed. Because of the overlap onto watersheds outside the Walnut Gulch watershed, this storm also could not be used to develop a conceptual model. Areal extent for varying isohyetal depths for the five model events are listed in Table 5.1. Average cross sections based on areal extent at each 0.5-inch contour for the five storms were plotted to show the similarity between maximum events (Fig. 5.14).

Rainfall of more than 2.5 inches in 30 minutes was recorded August 17, 1957 and September 10, 1967. During these two storms, greater rainfall volumes were recorded above 0.5, 1.0, 1.5, and 2.0 inches than for any of the other five major events. A composite maximum storm was constructed from 0.5-, 1.0-, 2.0-, and 2.5-inch isohyets for the 1957 storm and from the 1.5-inch isohyet for the 1967 storm. Actually, up to 1.5 inches, these two storms are almost identical. The higher peak discharge on August 17, 1957 than on September 10, 1967 resulted from much greater rainfall volume above 2.0 inches on August 17, 1957. The 1967 storm was also centered several miles farther from the watershed outlet, so there were greater channel abstractions.

Based on data from the Atterbury Watershed near Tucson, Fogel (1968) suggested that rainfall from individual thunderstorms appeared to be elliptical (when plotted by isohyetal mapping), but that the 1.5 to 1 ratio of long to short axis was small enough to assume circular

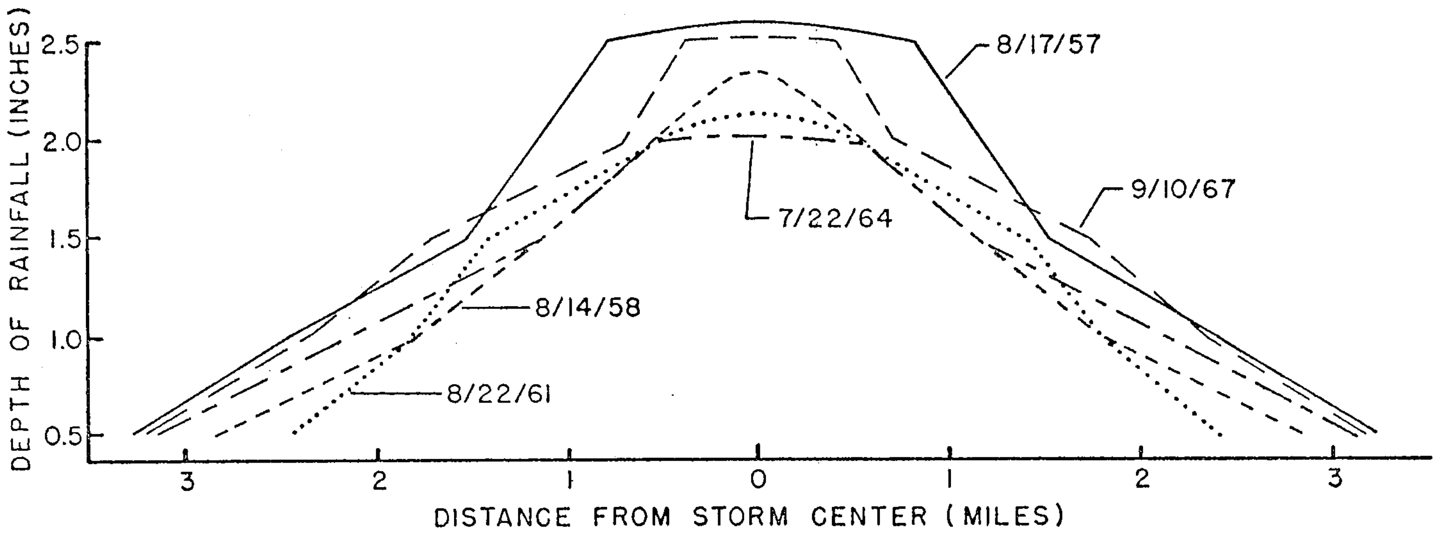

Fig. 5.14. Average cross sections for maximum 30-minute rainfall for 5 major runoff-producing thunderstorms, Walnut Gulch, 1955-1969

models. On Walnut Gulch, rainfall from individual thunderstorms appeared to be more elliptical with ratios of 2 or 3 to 1. However, the core of runoff-producing rainfall as represented by the maximum 30-minute depth of rainfall was less elliptical and closer to the 1.5 to 1 ratio that Fogel observed for total rainfall.

Two possible models of 30-minute rainfall were developed from the composite rainfall data from Table 5.1. Both were based on 32-, 18-, 9-, 4-, and 2-square-mile areas for the 0.5-, 1.0-, 1.5-, 2.0-, and 2.5-inch isohyets, respectively. One model consisted of circular isohyets with diameters of 6.4, 4.8, 3.4, 2.3, and 1.6 miles for the 0.5-, 1.0-, 1.5-, 2.0-, and 2.5-inch isohyets (Fig. 5.15). The resulting bell-shaped volume was extrapolated to a diameter of 8.4 miles for zero rainfall which appeared reasonable when compared to recorded events on Walnut Gulch. The area covered by rainfall of less than 0.5-inch in 30 minutes was not significant in predicting flood peaks, so only volumes above 0.5-inch in 30 minutes were used.

The second model was elliptical, with the major axis chosen as 1.5 times the minor axis (Fig. 5.16). Values for d and D, the minor and major axis, respectively, are shown in Table 5.2.

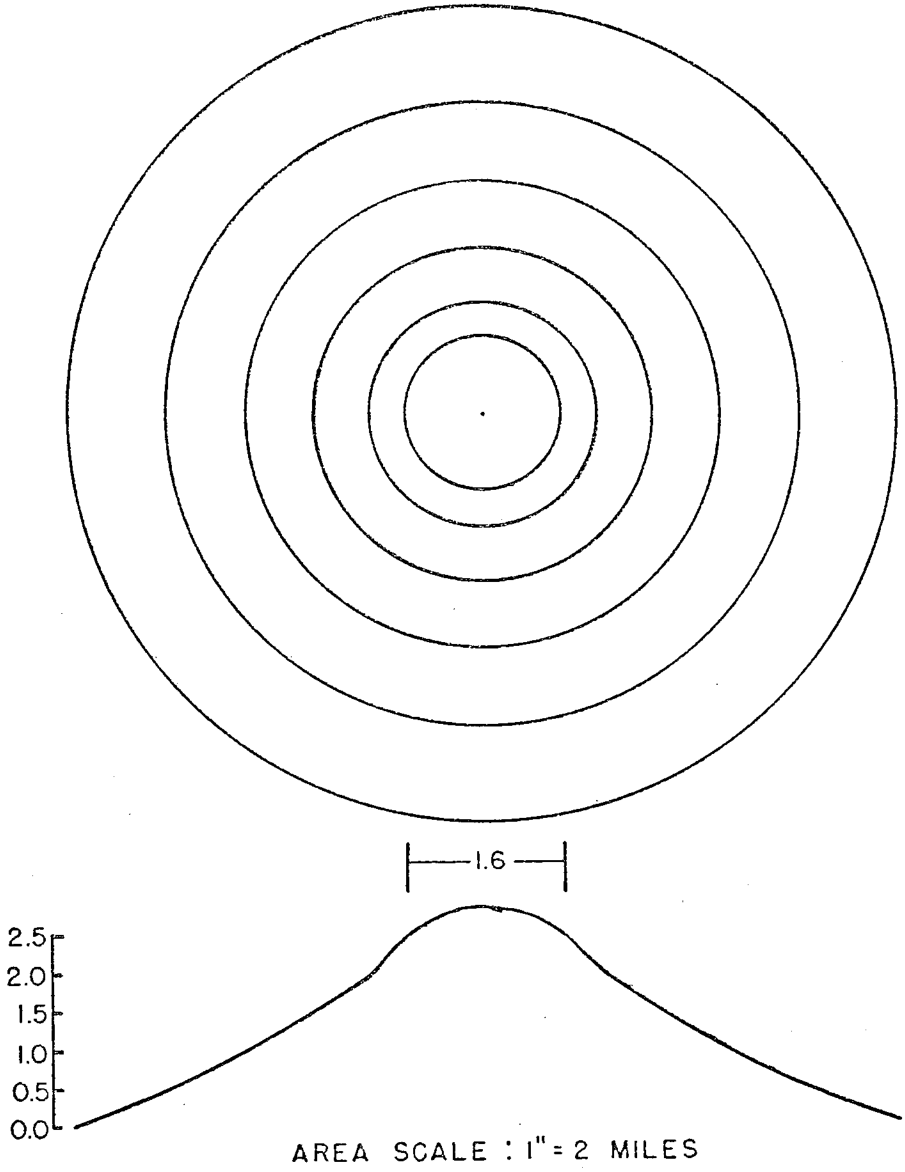

Fig. 5.15. Suggested circular model of maximum 30-minute rainfall for maximum expected thunderstorm rainfall, Walnut Gulch

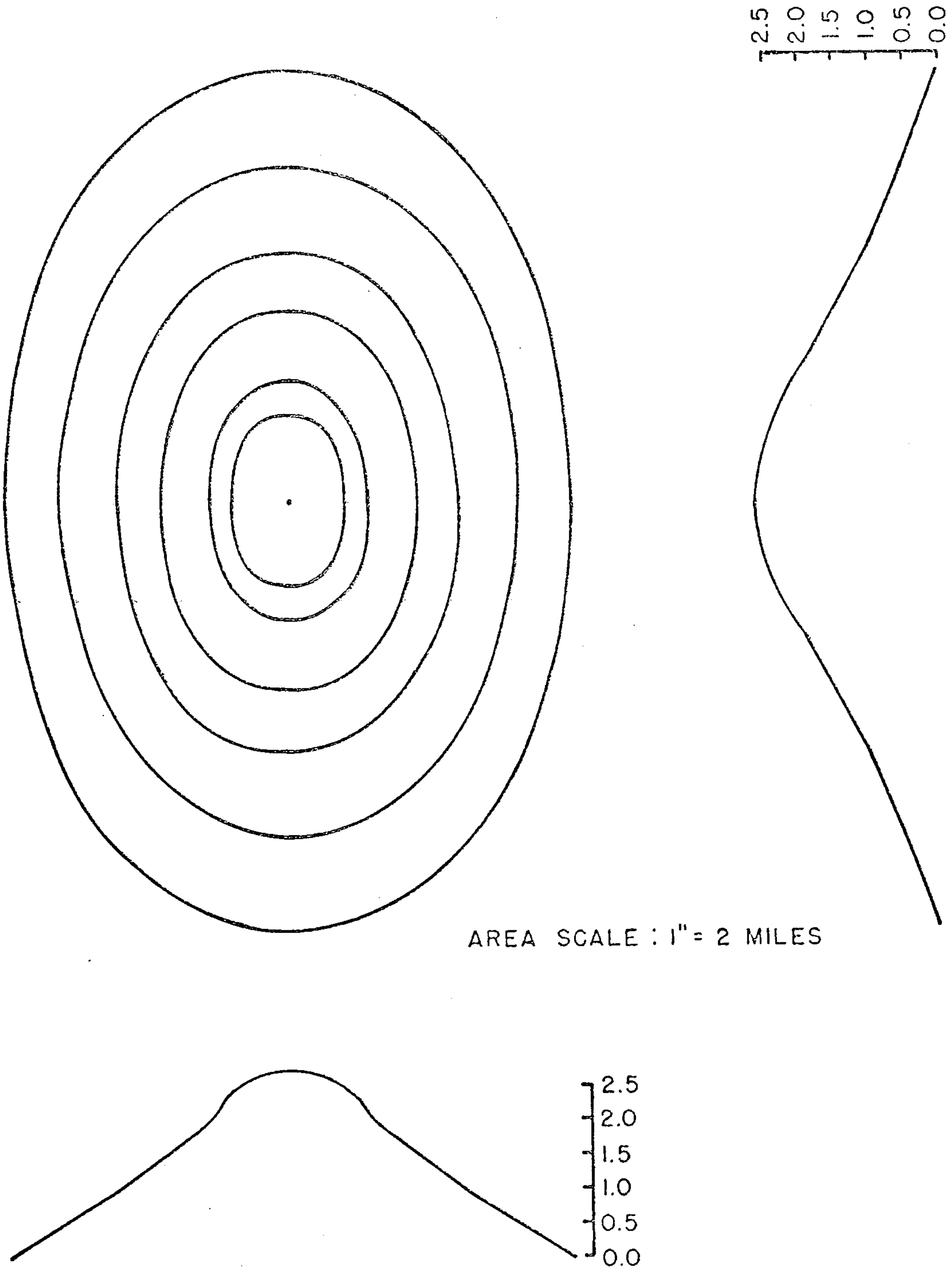

Fig. 5.16. Suggested elliptical model of maximum 30-minute rainfall for maximum expected thunderstorm rainfall, Walnut Gulch

Table 5.2. Shape factors for elliptical thunderstorm model

	Rainfall isohyet				
Area (sq. mi.)	0.5	1.0	1.5	2.0	2.5
Area (sq. mi.)	32.0	18.0	9.0	4.0	2.0
D (miles)	7.8	5.8	4.4	2.8	2.0
d (miles)	5.2	3.9	2.9	1.8	1.3

In general, data from both Walnut Gulch and other sources have indicated that rainfall patterns form a thunderstorm tend to be more elliptical than circular. However, the significance on small watersheds is uncertain. Also, for two major events on Walnut Gulch, isohyets with higher values (2.0 and 2.5 inches) appeared to be more circular than elliptical. However, an elliptical tendency is more common, and in this study, the elliptical model and the regression equations (Chapter 4) were used to predict the magnitude of the runoff peaks.

CHAPTER 6

THUNDERSTORM RUNOFF

In previous chapters thunderstorm rainfall and thunderstorm rainfall-runoff models were discussed. In this chapter the occurrence of thunderstorm runoff is investigated.

Runoff on Walnut Gulch, 1955-1969

The various subwatersheds of Walnut Gulch provide good examples of the effect of watershed size on thunderstorm runoff (Table 6.1). The average durations of runoff for 0.9-, 3.2-, 8.5-, 37-, and 58-square-mile watersheds for five years of record were 1.0, 5.4, 7.3, 4.6, 3.8 hours, respectively. The average duration of storm runoff per event for these five watersheds increased from 1 hour for the one-square-mile watershed (4) to approximately 7 hours for the 37-square-mile watershed (6), and then decreased approximately to 4 hours for the 58-square-mile watershed (1).

Some of the differences, between individual watersheds, however, were not because of differences in size. For example, many of the channels on the watershed 5 are underlain by relatively impervious conglomerates within a few inches, or feet, of the surface. The alluvium above these impervious layers is saturated relatively quickly. Recession low flows, rather than percolate to deeper levels, move downstream. This creates a longer recession on the hydrograph for

Table 6.1. Number and total duration of runoff events on several Walnut Gulch watersheds

Station	Area (sq.mi.)	1964 No. of events	1964 Total duration (hrs.)	1965 No.	1965 Total (hrs.)	1966 No.	1966 Total (hrs.)	1967 No.	1967 Total (hrs.)	1968 No.	1968 Total (hrs.)	Average No.	Average Total (hrs.)	Average duration per event (hrs.)
W-1	57.8	15	74	6	34	16	54	9	29	7	19	11	42	3.8
W-6	36.7	14	96	8	35	14	78	17	56	16	49	14	63	4.6
W-5	8.5	8	54	4	16	6	58	9	74	7	52	7	51	7.3
W-11	3.2	12	101	6	21	6	35	9	17	4	17	7	38	5.4
W-4	0.9	8	12	2	1	5	3	5	4	3	6	5	5	1.0

watershed 5 than is generally present on the other four watersheds. Also, for short periods of record, rainfall probably would not be random over the watersheds.

There are other differences in watershed characteristics, but there was an apparent real increase in average runoff duration from the one- to the 37-square-mile watershed, and an apparent real decrease from the 37- to the 58-square-mile watershed.

The average values for the annual number of events and the annual duration of runoff were also revealing. The fewest number of events and shortest duration of runoff were recorded on the smallest watershed. The average number of events and the average duration of annual (seasonal) runoff increased with watershed size up to the 37-square-mile watersheds, and then decreased for the 58-square-mile watershed.

Thunderstorm rainfall in southeastern Arizona occurs primarily in the afternoon and early evening. Runoff, naturally, follows rainfall, with more peak discharges occurring later in the afternoon and evening as watershed size increases. The 31 major runoff events (1955-1969) on the 58-square-mile watershed 1 occurred generally in the late afternoon and evening hours, with almost all peaks recorded between 4:30 p.m. and 1:30 a.m. (Fig. 6.1). By chance, only one major peak was recorded between 8:30 p.m. and 9:30 p.m.

All of the 31 major runoff events on watershed 1 occurred between July 15 and September 25 (Fig. 6.2), except for a storm on October 4, 1954. The 1954 storm produced a record peak discharge of 5,300 c.f.s. from watershed 5, and also produced a significant peak

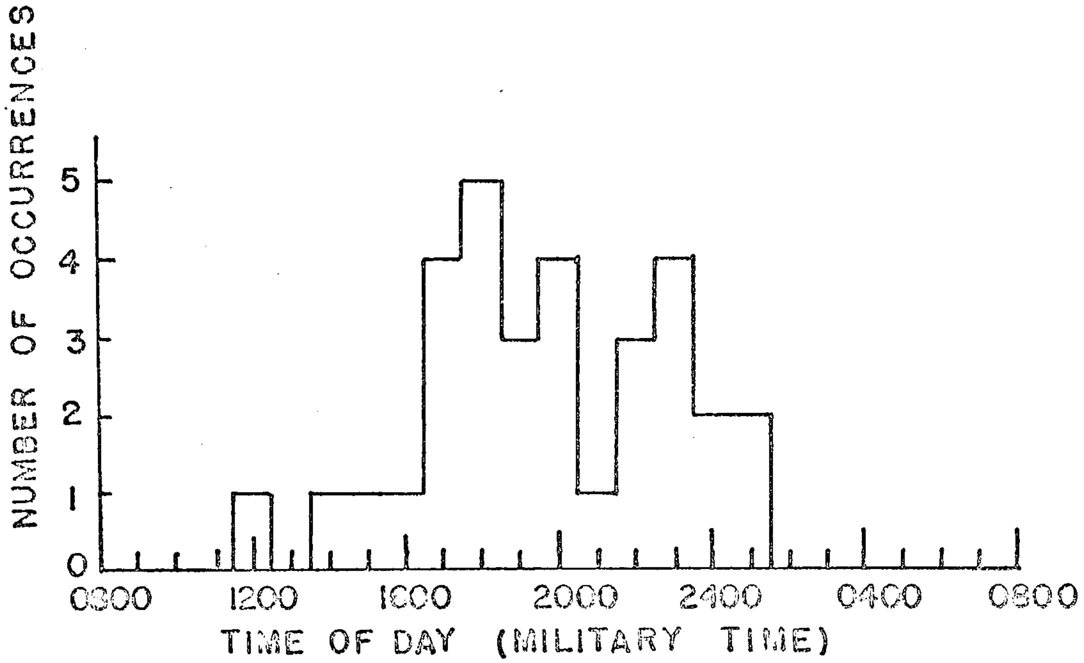

Fig. 6.1. Number of occurrences versus time of occurrence for 31 major flood peaks, Walnut Gulch, 1955-1969

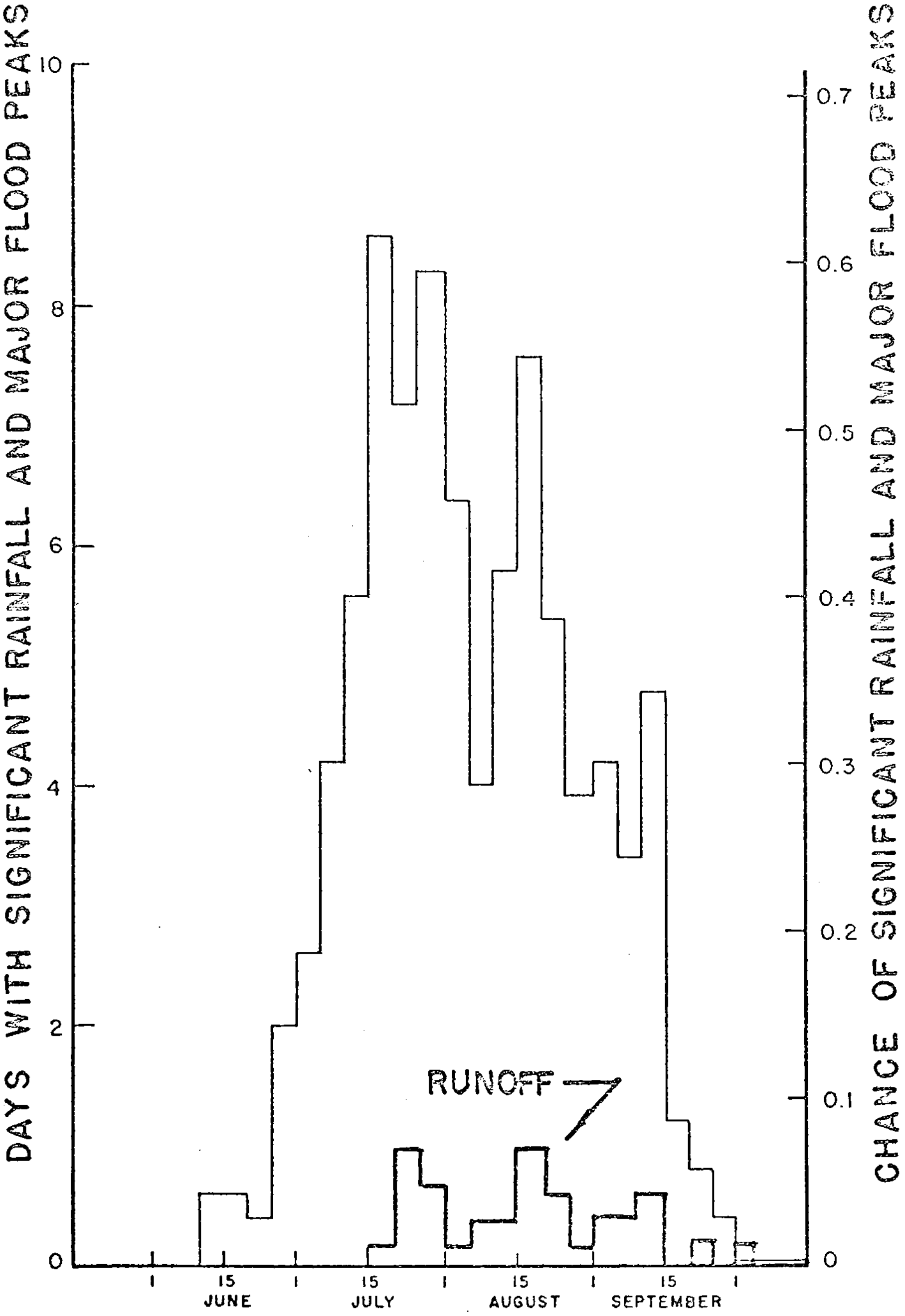

Fig. 6.2. Occurrence of significant rainfall and major flood peaks, Walnut Gulch, 1955-1969

discharge from watershed 1. Because of large transmission losses and the limited areal extent of the storm, however, the peak discharge from 1 was probably only about 2,000 c.f.s. which would rank it about twentieth on the list of major runoff events, and would not have changed the analyses for 1 significantly. Since the 1954 records were fragmentary for all stations, this storm was not included in the listing of major peak runoffs on watershed 1.

The seasonal occurrence of major runoff events on Walnut Gulch followed a similar pattern to that of significant rainfall, as would be expected. For 15 years of record there appeared to be three periods of increased thunderstorm runoff within the thunderstorm season--July 20-31, August 15-25, and September 1-15. As mentioned earlier, there may be a sound meteorological explanation for the observed variation, particularly for the increase in September (due to the occurrence of tropical storms off Baja California), but the record is too short to substantiate it.

There appeared to be about a 7 percent chance of a major runoff event occurring on any day between July 20 and 25 and August 15 and 20. On the other hand, there appeared to be less than a 2 percent chance of a major runoff event occurring between August 1 and 5 and August 25 and 31.

Three principal assumptions are made to predict thunderstorm runoff peaks in southeastern Arizona. First, the climatology and meteorology of southeastern Arizona will not change with time; that is, the same general thunderstorm conditions prevailed during the period of record and will continue to prevail in the future, or at least within the design life of the project. Without this assumption, any limits on the maximum possible runoff would be invalid. Second, data from Walnut Gulch are representative of thunderstorm runoff throughout southeastern Arizona. Third, the surface character of southeastern Arizona will not change with time.

Maximum Peak Discharge

Maximum Expected Peak Discharge, Walnut Gulch

An apt description was sought for the maximum expected peak discharge from a rangeland watershed in southeastern Arizona. Such terms as "probable" and "possible" are used in the literature. However, a more appropriate description for the maximum design peak discharge, which is based primarily on known rainfall and runoff records in southern Arizona might be the "maximum expected peak discharge (WG)," where "WG" stands for Walnut Gulch.

The maximum expected peak discharges for watershed 1 (57 square miles) and watershed 5 (8.5 square miles) were determined from a combination of known rainfall records in Arizona, the model for maximum expected rainfall which was developed from Walnut Gulch rainfall data, and the rainfall-runoff relationships also derived from Walnut Gulch records. The equation used for watershed 1 was the same as Equation 4.24, except that C and R equalled one, and $0.30V_{30}$ was added.

$$Q_a = 0.02 + 0.01V_{10} + 0.01V_{15} + 0.03V_{20} + 0.15V_{25} + 0.30V_{30} \qquad (6.1)$$

There were several assumptions that were essential to the goodness of the estimates of maximum expected peak discharge (WG). First, the maximum point rainfall that is expected to occur on Walnut Gulch in 30 minutes is 3 inches. Second, the Walnut Gulch rainfall model developed in Chapter 5 is a good estimate of runoff-producing thunderstorm rainfall. Third, the rainfall-runoff relationship developed in Chapter 4 can be extrapolated, within reason, to greater values than those used in deriving the equations. Fourth, the maximum expected peak discharge will occur in a relatively dry channel. Fifth, differences in infiltration rates for rangeland watersheds in relatively dry conditions do not appreciably affect maximum peak discharges.

Fogel and Duckstein (1969) reported that a thorough search of U.S. Weather Bureau data for Arizona indicated that no known gage had ever recorded over 4.5 inches of rainfall during a 24-hour period. The maximum for a single storm on the Atterbury watershed was about 2.5 inches. They did not comment on shorter durations. A thorough search of U.S. Weather Bureau data for Arizona did not uncover a gage where over 2.65 inches of rainfall had been recorded in one hour other than on Walnut Gulch. The maximum one-hour point rainfall on Walnut Gulch was 3.5 inches on September 10, 1967. The maximum 30-minute rainfall for the same storm at the same point was 2.52 inches. Between 2.5 and 2.65 inches of rainfall in 30 minutes was recorded at three points almost simultaneously on August 17, 1957. Also, just over 2.5 inches of rainfall in 30 minutes was recorded at 2 rain gages on Walnut Gulch on October 4, 1954. These are the only known occurrences of rainfall exceeding 2.5 inches in 30 minutes on Walnut Gulch in 15 years of record. If each U.S. Weather Bureau recording rain gage is assumed an independent sampling point, there are about 1,000 gage-years of record in southern Arizona. If all recording gages on Walnut Gulch are independent points, there are also about 1,000 gage-years of record from Walnut Gulch. The U.S. Weather Bureau record for southern Arizona includes several stations with 30 or more years of record and about 30 stations with 20 to 30 years of record. One might expect to find greater recorded intensities in the U.S. Weather Bureau record, since it generally covers a longer period, a wider range of topographic and climatic locations, and the stations are almost certainly independent sampling points, at least for sampling air-mass thunderstorm rainfall. Yet, three separate events on Walnut Gulch greatly exceeded anything recorded at USWB recording rain gages in southern Arizona. This fact suggests that something other than chance is responsible for the difference between the 1,000-gage-year USWB record and the 1,000-gage-year Walnut Gulch record.

Two possible explanations are that (1) southeastern Arizona experiences more air-mass thunderstorm rainfall than occurs in south-central and southwestern Arizona, and that (2) the gages on Walnut Gulch are independent points, at least for sampling "record" rains, and the dense network on Walnut Gulch is, in some way, a more efficient "measure" of maximum point rainfall than is the 1,000-gage-year USWB record.

For the first hypothesis, summer rainfall as recorded at USWB stations generally decreases from east to west across southern Arizona. In general, the elevation of the recording rain gage stations also decreases from east to west across southern Arizona, which may be the primary reason for decreasing rainfall. For example, Walnut Gulch gages (4,000-6,000 feet) record about 60 percent more summer rainfall than Tucson (2,600 feet). The three long term (over 30 years) USWB recording stations in southern Arizona are Tucson (2,600 feet), Phoenix (1,100 feet), and Yuma (near sea level), and there is considerably less summer rainfall at Phoenix than at Tucson, and much less at Yuma than at Phoenix. Also, Walnut Gulch is closer to the prime source of summer moisture, the Gulf of Mexico.

It is difficult to argue that the 1,000-gage-year record for Walnut Gulch is a more efficient "measure" of maximum point rainfall than the 1,000-gage-year record for southern Arizona. At present, it seems that some element of chance combined with more summer rainfall on Walnut Gulch is the probable answer. However, one might say that the network of rain gages on Walnut Gulch represents a 58-square-mile "rain gage" located in a region that receives more summer rainfall than do most USWB recording rain gage stations in southern Arizona.

Therefore, the Walnut Gulch assumptions for intensities from short duration air-mass thunderstorms--those which produce maximum peak discharges from small watersheds in the southwest--may be, if anything, on the "safe" side for design purposes for watersheds at elevations of less than 6,000 feet throughout southern Arizona. Walnut Gulch records suggest that on a 58-square-mile watershed in southeastern Arizona air-mass thunderstorm rainfall of 2.5 inches or more in 30 minutes might be expected about once in five years. Rainfall of 2.75 inches or greater in 30 minutes has never been recorded on Walnut

Gulch or at any USWB recording rain gage in southern Arizona. (No storms with such magnitudes of short duration rainfall as those recorded on Walnut Gulch have been measured at USWB recording rain gages in northern Arizona, as well.)

Reich and Heimstra (1965) felt that 30 minutes was the proper duration for correlating thunderstorm rainfall and runoff on small watersheds (1.5 to 5 square miles). Other reasons for using 30-minute duration were discussed in Chapter 4. The final decision to use 3 inches in 30 minutes as the maximum expected point rainfall was somewhat arbitrary, but was influenced by the aforementioned facts.

The validity of predictions of maximum expected peak discharges for Walnut Gulch is dependent upon the validity of the rainfall model developed in Chapter 5. For comparison, assuming that rainfall models developed by Woolhiser and Schwalen (1959) and Fogel and Duckstein (1969) apply to the maximum 30-minute rainfall as well as total storm rainfall, the three models were plotted together for the 3-inch design rainfall (Fig. 6.3). The models were obviously quite similar, but the Walnut Gulch model was appreciably more slender. The importance of the differences was indicated when peak discharges were calculated. The maximum expected peak discharges as determined by Equation 6.1 for the 57-square-mile watershed were 23,000 c.f.s., 33,000 c.f.s., and 35,000 c.f.s. for the Walnut Gulch, Woolhiser-Schwalen, and Fogel-Duckstein models, respectively.

However, it would seem logical that models for 30-minute rainfall for the Atterbury watersheds would be more slender than the models

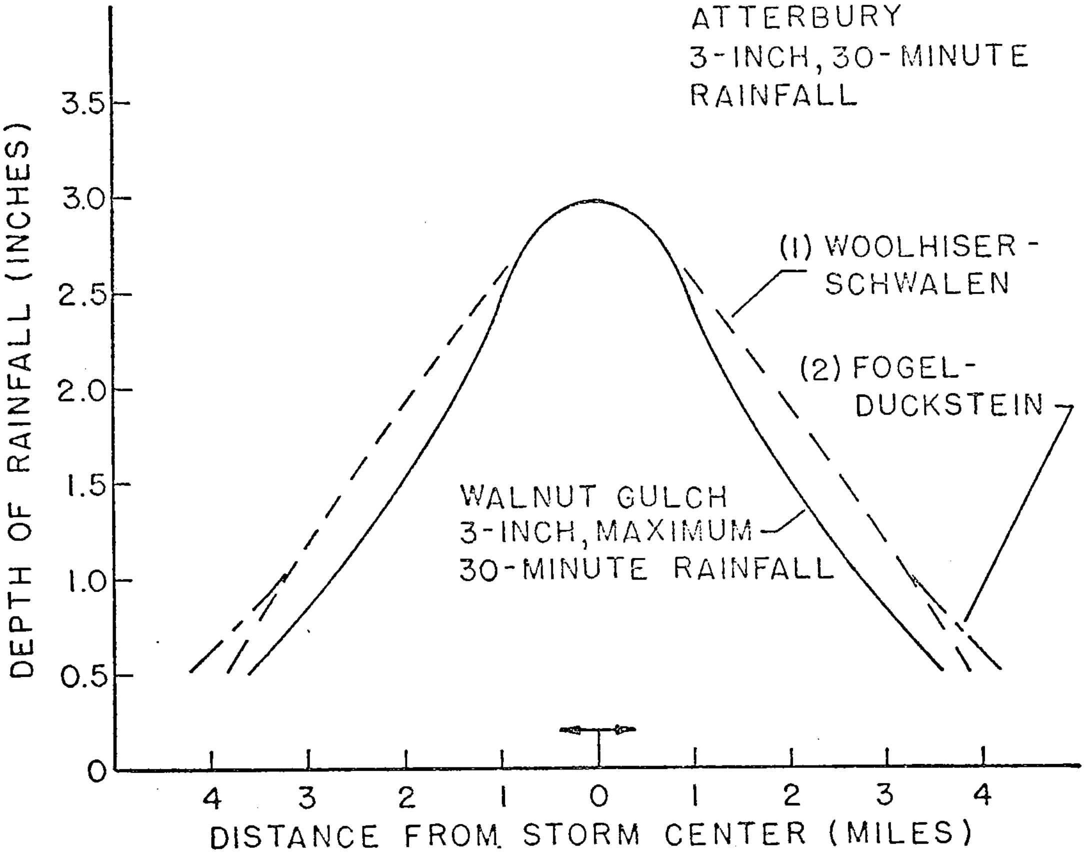

Fig. 6.3. Comparison of Woolhiser-Schwalen, Fogel-Duckstein, and Walnut Gulch rainfall models for a 3-inch, 30-minute rainfall

for storm totals, since this was apparent when total rainfall was compared to maximum 30-minute rainfall on Walnut Gulch.

Most designers would be happy with a range of 23,000 to 35,000 c.f.s. for a design peak discharge. However, the answer isn't quite that simple, since if either of the Atterbury models is the "correct" model, the question of accuracy must be applied to 33,000 or 35,000 c.f.s. The maximum expected peak discharge of 23,000 c.f.s. could be in error by 50 percent and still not exceed 35,000 c.f.s. while a 50-percent error on 35,000 c.f.s. would suggest a possible maximum expected peak discharge of over 50,000 c.f.s. Although this may still be as close as one can hope for under the circumstances, further effort in justifying the Walnut Gulch model as opposed to the Atterbury watersheds might be warranted.

For the 8.5-square-mile watershed 5, the maximum expected peak discharge, using the 3-inch in 30 minute rainfall and Equation 4.26 was 17,000 c.f.s. The equation used was similar to Equation 4.26.

$$Q_a = 0.05 + 0.10V_{10} + 0.15V_{15} + 0.40V_{20} + 0.60V_{25} + 0.80V_{30} \qquad (6.2)$$

Maximum Expected Peak Discharge, Southwest

The maximum expected peak discharge (SW) is defined as that discharge which could occur on Walnut Gulch from a greater than expected 30-minute rainfall as determined from records from Arizona and New Mexico. The greater rainfall would be unlikely to occur, but could not be considered impossible. The equation for watershed 1 was similar to Equation 4.24.

$$Q_a = 0.02 + 0.01V_{10} + 0.01V_{15} + 0.03V_{20} + 0.15V_{25} + 0.30V_{30} + 0.45V_{35} \quad (6.3)$$

Essentially the same assumptions are made to determine the maximum expected peak discharge (SW) as are made to determine the maximum expected peak discharge (WG), except that rainfall records from New Mexico as well as Arizona are included in determining the magnitude of the maximum point rainfall at the storm center. Also, the question of the effect of overbank flow on peak discharge and the reliability of rainfall-runoff relationships when applied to overbank flow are considered.

Benson (1964), Reich and Hiemstra (1965), and Fogel (1968) and others have pointed out that floods from small rangeland watersheds (such as Walnut Gulch) result from short-duration, high-intensity thunderstorm rainfall. Fogel (1968) stated that thunderstorm runoffs occurring about 24 or more hours after a previous runoff were relatively unaffected by antecedent conditions. For 15 years of record on Walnut Gulch, all "record" peak discharges have occurred after at least several relatively dry days.

It was stated in U.S. Weather Bureau Technical Paper 38 (1960) that extreme events could occur no more often than 4 or 5 days apart. This referred to frontal activity which, as will be shown later, is important in determining the maximum expected peak discharge (SW). As described in Chapter 4, for air-mass thunderstorms, heavy rainfall on one day tends to decrease the potential for extreme events to occur on following days. Antecedent conditions were therefore excluded from determinations of maximum expected peak discharges.

The maximum known 30-minute rainfall recorded on a recording rain gage in the Southwest was 3.5 inches on Alamogordo Creek in northeastern New Mexico. The rainfall resulted from combined convective heating and a weak, fast-moving cold front moving across the watershed on the afternoon of June 5, 1960. The combination of available moisture, convective heating, and frontal activity appeared ideal for producing an extreme thunderstorm rain.

On Alamogordo Creek, there were four storms in 15 years in which over 3.0 inches of rainfall was recorded in 30 minutes at one or more points on the watershed. This suggests a recurrence interval for such an event of about four years. Point rainfall of over 3.0 inches has been recorded nine times in 15 years and about 800 gage-years of record. This suggests a point recurrence interval for a rainfall of over 3 inches in 30 minutes of about 100 years. No storms in which 3.0 inches or more was measured have been recorded at USWB recording rain gages in New Mexico. There are fewer recording rain gages in New Mexico than in Arizona, and the network of rain gages on Alamogordo Creek is less dense than the one on Walnut Gulch. The occurrence of four "greater than 3.0-inch" storms on Alamogordo Creek and none greater than 2.75 inches on Walnut Gulch would appear to be for some unknown reason other than chance.

Reich and Hiemstra (1965) and Fogel and Duckstein (1969) both cut off their rainfall predictions at 5 inches in one storm. Their justification for doing so was based on available rainfall records and was to some extent arbitrary. No recorded rains of more than 3 inches in 30 minutes were reported in either of the two papers.

The best available information on extreme rainfall events is the U.S. Weather Bureau. Unfortunately, there are relatively few good estimates of extreme rainfall in the Southwest. As discussed in Chapter 2 in U.S. Weather Bureau Technical Paper 38 (1960), the probable maximum 1-hour rainfall for southern Arizona was estimated as 12 inches. This value was not based on theoretical atmospheric conditions, but on recorded historical events. At first, this appeared to be more desirable, as one might put more confidence in such records than in a theoretical development. However, a thorough search of the literature led to considerable uncertainty as to the reliability of the estimate for maximum probable precipitation in southern Arizona.

The following statements are from U.S. Weather Bureau Technical Paper 38 (1960).

> The occurrence of outstanding thunderstorm rainfall at Fort Mohave, near the Arizona-Nevada border, and of other severe storms throughout Arizona is believed to justify transportation of the Campo (California) storm throughout this entire region south of the first major orographic barrier (p. 50).

The Fort Mohave record (1898) was described as follows:

> On the 28th we had the biggest rain in 10 or 15 years, and to my regret, between the rain and furious wind, my rain gage was upset. To give an idea of the amount of rain that fell, and which lasted only 45 minutes, I had a wash tub set out on the mesa, clear of everything, and the water, after the rain, measured 8 inches (p. 58).

The reference to "other severe storms throughout Arizona" in the first quotation was apparently a general statement since no other Arizona records approached the magnitude of the event reported from Fort Mohave in 1898. There was a report of 8 inches of rainfall in two hours in the White Mountains on July 19, 1955. Also, Lewis (1963) reported close to 7 inches of rainfall in one frontal-convective storm (two bursts--about 12 hours apart) near Tucson, Arizona. Justification for transposing the fairly well documented Campo, California storm across southern Arizona appears to be weak.

Therefore, 3.5 inches in 30 minutes was chosen as the maximum runoff-producing rainfall that could occur if the same atmospheric conditions that can occur in eastern New Mexico did occur in southeastern Arizona. As stated, this is unlikely, but cannot be ruled as impossible.

The 3.0-inch and 3.5-inch rains are shown in Figure 6.4. The estimated expected peak discharge (SW) for watershed 1, based on extrapolation of rainfall-runoff Equation 4.24 developed in Chapter 4 would be 54,000 c.f.s. This estimate depends on the reliability of Equation 4.24 for overbank flow and the reliability of the rainfall model developed in Chapter 5, as well as the possibility of such a storm occurring.

It is difficult to determine the effect of overbank flow on peak discharge. However, the increased storage should decrease the estimated peak discharge appreciably. A reduction of 25 percent, which is not unreasonable, would indicate a peak discharge of about 40,000 c.f.s. Without a complete study of the channel and overbank hydraulics, a more accurate estimate is impossible.

For comparison, the 3.5-inch rain on June 5, 1960 on Alamogordo Creek, which was used to predict the maximum expected peak discharge (SW) on Walnut Gulch, produced a peak discharge of possibly 10,000 c.f.s. on the 67-square-mile Alamogordo Creek watershed. However, the channel slopes are only about 25 percent as steep as those on Walnut

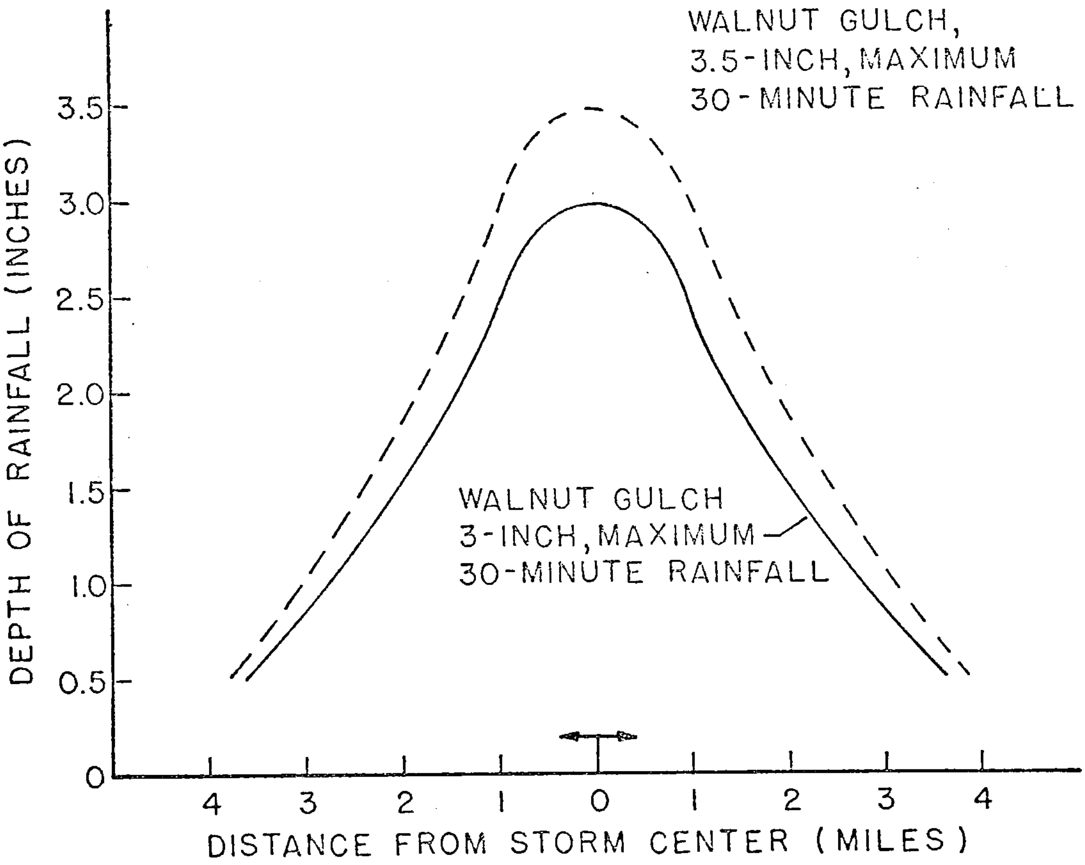

Fig. 6.4. Comparison of 3- and 3.5-inch rains with Walnut Gulch model

Gulch, and the channel capacity about one mile upstream from the gaging station is only a few thousand c.f.s. Major flows spread out over large areas, thus decreasing peak discharges tremendously.

The effect of overbank flows on Walnut Gulch (over about 15,000 c.f.s.) should be considerably less than on Alamogordo Creek, but still very appreciable. A search of the literature suggests that further studies on overbank discharges are warranted, since very little information is available in this area.

Recurrence Intervals

For watersheds 1 and 5, maximum annual peak discharges versus recurrence intervals were plotted, and the maximum expected peak discharges (WG) were indicated (Fig. 6.5). Smooth curves based on the plotted points and the limits indicated by the maximum expected peak discharges were then constructed by eye. Estimates of recurrence intervals for storms with various peak discharges could be made from these two curves for watersheds of various sizes (approximately 3 to 60 square miles). The shape of these magnitude-frequency curves would tend to put most engineering hydrology problems into one of two categories. One would be designs based on frequent floods--about 10 years or less--with a check on what might happen with a larger, rarer, flood. The other would be designs for which the loss due to failure is relatively great--unacceptably--in which case the maximum expected flow (WG) or the maximum expected flow (SW) would be reasonably conservative estimates.

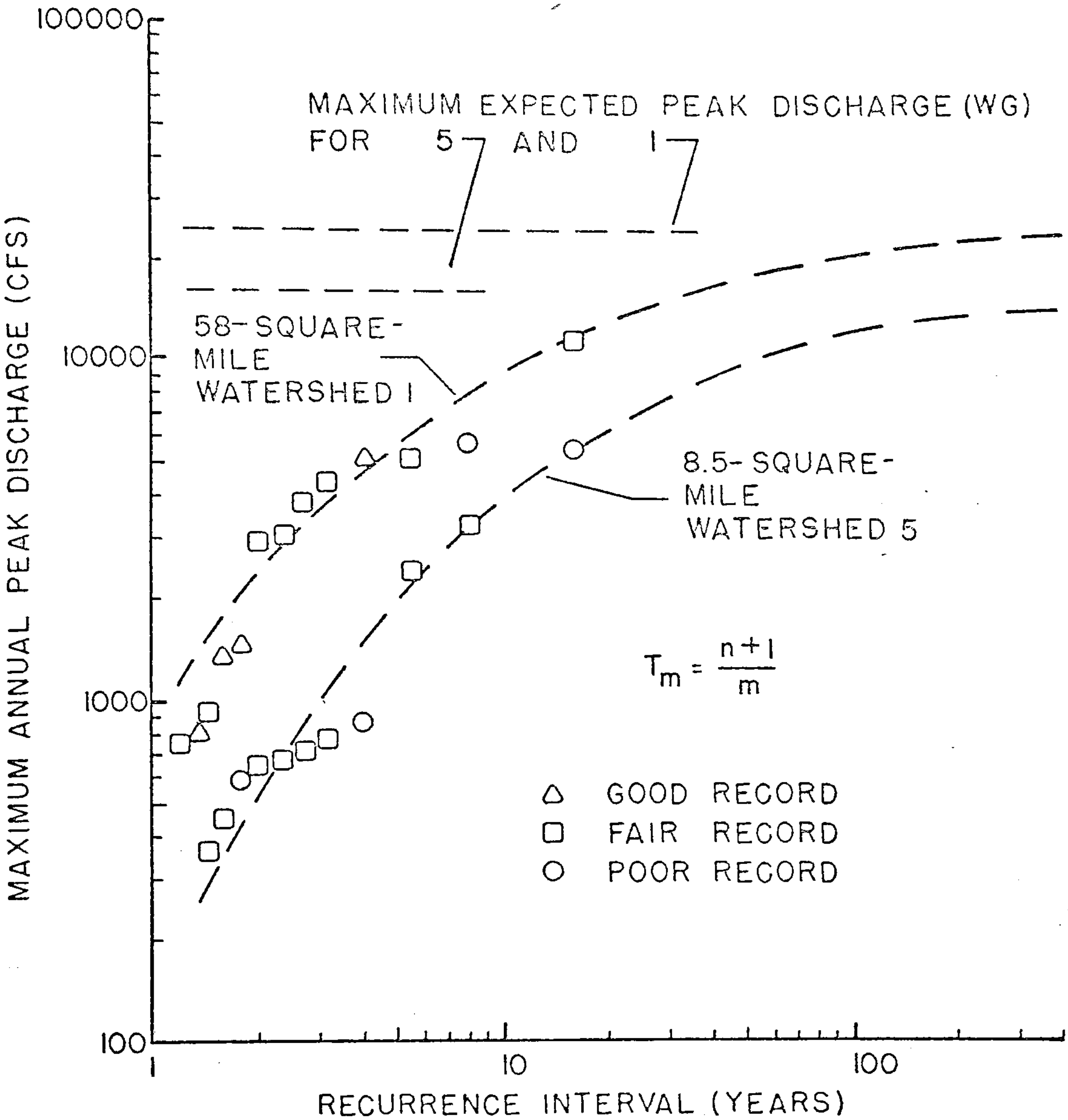

Fig. 6.5. Maximum annual peak discharges versus recurrence interval for watersheds 1 and 5, Walnut Gulch

In Chapter 2, flood peaks in Arizona were compared. In Figure 6.6, Figure 2.1 from Chapter 2 has been duplicated, with the maximum expected peak discharges and the estimated 10-, 20-, 50-, and 100-year storms drawn in. The estimate for the maximum expected peak discharge (WG), for watersheds of less than 100 square miles, encompasses all but one of the "record" events for small watersheds in Arizona. The one higher peak was a "miscellaneous flood observation" made near Yuma, Arizona.

A possible use for Figure 6.6. would be to estimate the recurrence interval for an exceptional event on a watershed with relatively short record. For example, a maximum peak discharge of 5,000 c.f.s. has been recorded in 8 years on watershed 11 (3 square miles) on Walnut Gulch (see Fig. 3.5). Peak discharges determined from Figure 6.6 for 10-, 20-, 50-, and 100-year storms and the maximum expected peak discharge (WG) were plotted on Figure 6.7. A smooth curve was drawn through the points, and the maximum recorded 8-year storm was plotted. The estimated recurrence interval for the maximum recorded storm was on the order of 25 years, as indicated by the arrow. Also, the maximum recorded peak discharge was about one-half of the maximum expected peak discharge (WG).

Peak discharge per unit area decreased more rapidly with increasing watershed size for the family of curves based on Walnut Gulch data than for the family of curves indicated in Figure 2.1 which is the usual Q/A versus $\sqrt{A}$ relation. This suggests that there may be two families of curves; one for the small watersheds where air-mass

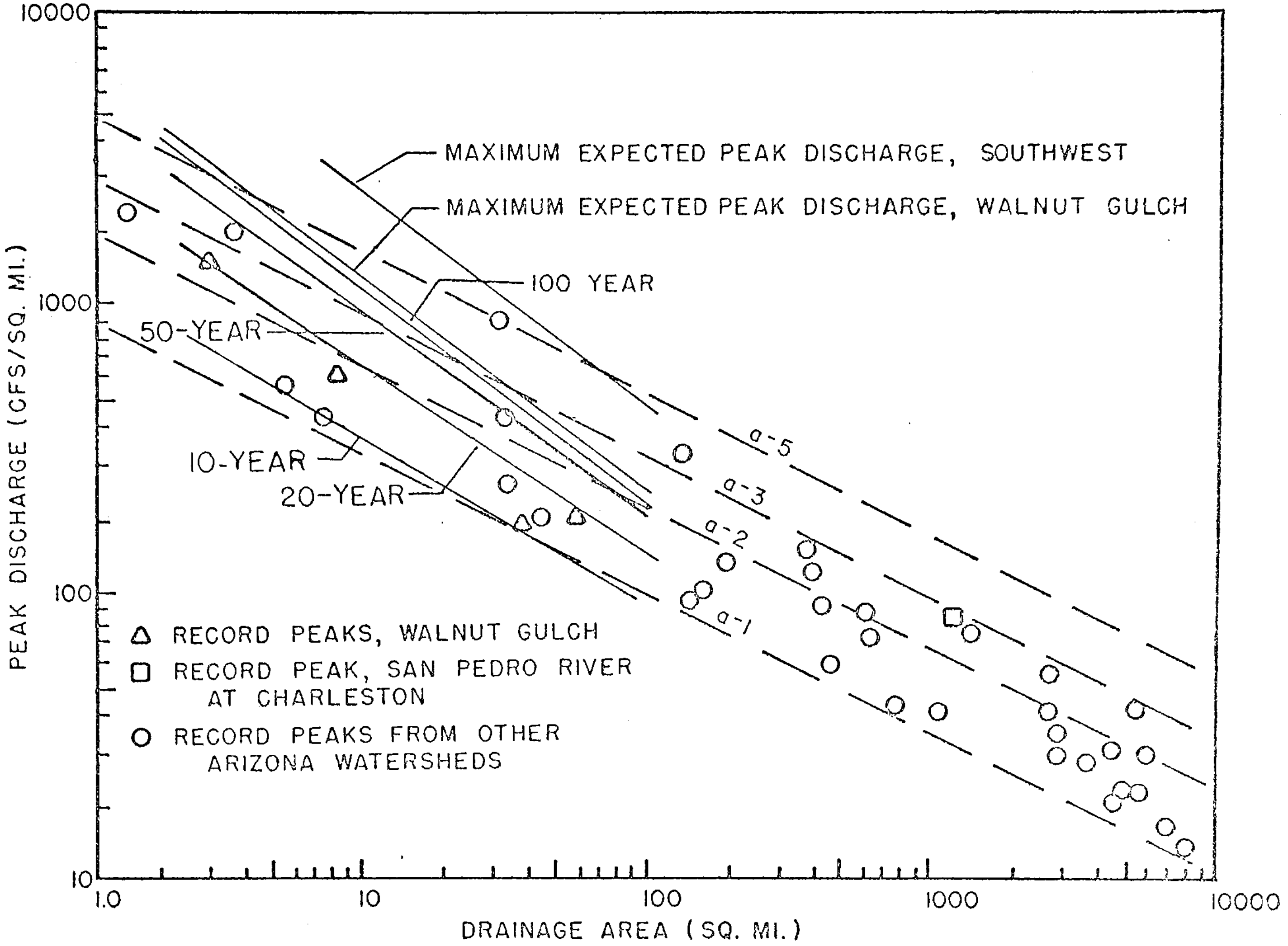

Fig. 6.6. Comparison of estimated maximum expected peak discharges and estimated 10-, 20-, 50-, and 100-year peak discharges for Walnut Gulch with peak discharges versus drainage area for Arizona flood peaks

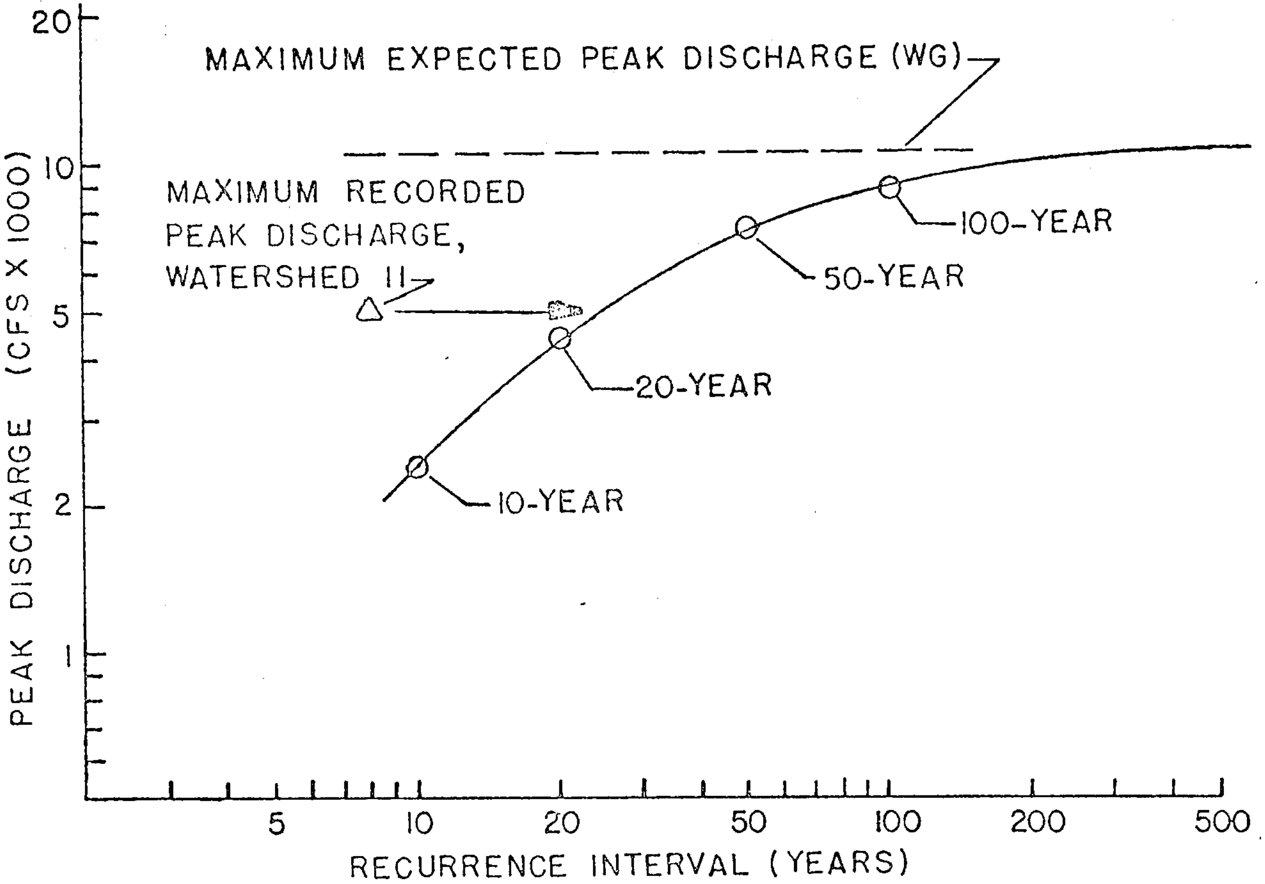

Fig. 6.7. Estimation of recurrence interval for the maximum recorded peak discharge from watershed 11, Walnut Gulch

thunderstorms dominate peak discharge, and the other for large watersheds where snowmelt or frontal-convective storms produce the major flood peaks. The curves probably intersect between 100 and 1,000 square miles. For runoff design for intermediate sized watersheds two probability estimates may be needed--the probability of storms of certain intensities falling on most of the watersheds, and the probability of more intense storms developing over several tributaries of the watershed in such patterns as to produce "record" peak discharges.

CHAPTER 7

RISK, UNCERTAINTY, AND ERROR

In Chapters 4 and 5, rainfall-runoff relationships and rainfall models were developed primarily from data from Walnut Gulch. In Chapter 6, maximum peak discharges were estimated from equations and models developed in Chapters 4 and 5. There are uncertainties and possible errors in these models and equations which should be understood before they are used in design.

Uncertainty of Recurrence Interval

There are essentially two types of risk involved with recurrence intervals. The first assumes that the recurrence intervals for various magnitudes of flow have been correctly determined, but that there is a risk that the design storm may occur at any time, rather than at regular intervals. The engineer must decide what losses will occur if the design flood is exceeded, and assess the probability that these greater flows will occur during the life of the structure.

There is also risk because of uncertainty in the estimated recurrence interval for a given flood discharge. As Bell (1969) pointed out, the actual recurrence interval for a 100-year event may range from well under 50 years to several hundred years, depending on the length of record; and, all records are too short to limit the range within 50 to 200 years. For example, there were only 15 years of Walnut Gulch data from which to make these analyses, so the estimated 100-year event may have a real recurrence interval of anyplace from 20 to 30 years to several hundred years.

Finally, recurrence intervals are determined from data that may contain appreciable errors. For example, the maximum recorded peak discharge from Walnut Gulch for 15 years of record was 11,500 c.f.s. This peak was estimated to be within no worse than plus or minus 15 percent, or the actual maximum peak discharge was no greater than 13,000 c.f.s. or less than 10,000 c.f.s. The possible range in the recurrence interval, from Fig. 6.5, would then be about 10 to 22 years. The possible range for the 15-year flood within 95 percent confidence limits assuming a normal distribution of error would be 9,500 to 13,500 c.f.s. Without the assumption of normality, the range would be 7,500 to 15,500 c.f.s.

However, as illustrated in the first three chapters, predictions of peak discharge for the 100-year flood on Walnut Gulch range from 12,000 to 35,000 c.f.s. depending upon the chosen frequency distribution. Assuming the worst possible distribution of errors within the 95 percent confidence limits (about a plus or minus 33 percent) the range would increase to 8,000 to 47,000 c.f.s. Thus, knowledge of the correct distribution would appear to be extremely important as the spread of the estimate is greater for different distributions than for the probable error in the measured data.

Error of Estimate

If a limit can be set on the maximum peak discharge, the possible range of values for floods of given recurrence intervals is also constrained. More important, if the limit forces the curve of peak discharge versus recurrence interval to bend abruptly with an asymptotic approach to the limit, the need for, or usefulness of, the estimate of the 50-year or 100-year flood, for example, will be greatly reduced.

Since a major conclusion of this study includes estimates of maximum peak discharge, the possible range of error of these estimates must be considered. Possible errors generally are of two types--(1) errors in the data, and (2) errors in the models. Accuracy of the regression equations depends largely on accuracy of estimates of rainfall volumes and peak discharge for a few extreme events, and on the accuracy with which the model represents the true physical processes. Yen (1970) described these errors in the context of risk and uncertainty. "These risks and uncertainties include the risk due to limited available data and the uncertainties include the risk due to limited available data and the uncertainties arising from transformation of rainfall data to runoff information, from using a point record to represent an area, ..., and from the uncertainty of the mathematical techniques on handling the data and measurement errors" (p. 963).

Errors in measuring peak discharge, particularly the few major peaks, are directly transmitted to the rainfall-runoff equation. The effect of errors in estimating rainfall volumes is more subtle. The fraction of rainfall volume contributing to peak discharge increases with increased rainfall depth, but the volume of rainfall above each succeedingly higher depth decreases. Also, because there were a large number of measured points within the runoff-producing rainfall, errors in rainfall volumes between and within each 0.5-inch level are not apt to be cumulative, and may be compensating. Therefore, in the prediction equations "plus" errors would not be carried through all the rainfall volumes, V_{10}, V_{15}, V_{20}, and V_{25}, but would probably apply only to one of the four volumes.

The possible errors in the estimate for maximum expected peak discharge for Walnut Gulch 1 (58-square-miles) were investigated in two ways. First, the sample of 30 points was divided randomly 8 times into equal 15 point records. Coefficients for V_{10}, V_{15}, V_{20}, and V_{25} in the equation $Q_a = 0.02 + bV_{10} + CV_{15} + dV_{20} + eV_{25}$ were varied until the maximum R^2 was found for each of the eight, 15-point samples. Then the second half of each sample was used to determine the R^2 and the standard error of the estimate of the predicted versus actual peak discharges, and to predict the maximum expected peak discharge (WG)(Table 7.1). Coefficients of b, c, d, and e varied from 0.008 to 0.010, 0.010 to 0.015, 0.020 to 0.025, and 0.120 to 0.170, respectively, and the estimate of the maximum expected peak discharge (WG) varied from 19,000 to 25,000 c.f.s. with the estimate from the full sample 23,000 c.f.s. The range of predicted maximum peaks was less than might have been expected. Obviously, different sets of 15 points would give different results, but this nontheoretical random test did suggest that the data were generally good and that the rainfall-runoff equation as developed for watershed 1 was consistent.

Table 7.1. Range of values for coefficients in the regression equation $Q = a + bV_{10} + dV_{15} + dV_{20} + eV_{25}$ and predicted maximum peak discharge for watershed 1, Walnut Gulch

Trial	a	b	c	d	e	Trial	R^2	S.E.E. (cfs/acre)	Pred. Max. (cfs)
8-1 *	.020	.010	.010	.020	0.150	8-2	.54	.029	22,000
9-1 *	.020	.010	.012	.022	0.140	9-2	.56	.031	22,000
10-1 **	.020	.010	.010	.020	0.120	10-2	.87	.030	20,000
11-1 *	.020	.008	.014	.023	0.140	11-2	.47	.034	19,000
12-1 *	.020	.008	.014	.022	0.140	12-2	.56	.031	19,000
13-1 **	.020	.010	.015	.025	0.170	13-2	.80	.038	25,000
14-1 **	.020	.010	.010	.020	0.120	14-2	.88	.032	20,000
15-1 **	.020	.008	.010	.020	0.140	15-2	.83	.037	21,000

* Equation developed included storm of 8-17-57

** R^2 and SEE include storm of 8-17-57

Second, David and Neyman (1938), Draper and Smith (1966), and others have suggested methods for determining variances for predicted values from regression equations of the form $Y = k + C_1X_1 + C_2X_2 + \dots C_nX_n$. These methods employ least squares fitting of the sample data. The methods generally indicate the variance of the mean of the predicted value, since the variance of the mean is what is usually wanted by statisticians. Hydrologists and engineers, however, are quite often interested in the variance of an individual predicted value.

In this section, the variance of the mean predicted value is estimated, using matrix methods described by David and Neyman (1938). Then the variance about the regression line, calculated as the sum of squares of residuals over the residual degrees of freedom, is used to convert the variance of the mean predicted value to the variance for a single predicted value.

Using matrix notation from Draper and Smith (1966), the mean predicted value assuming normality and the desired confidence limits is

$$Y = \hat{Y} \pm t(v, 1 - 1/2\alpha) \cdot s \sqrt{1/n + X_o' CX_o}$$

where Y = the predicted value

n = number of observations

s = standard deviation about the regression line, calculated as the square root of the sum of squares of residuals over the residual degrees of freedom

X_o = column vector for specific value

$C = (X'X)^{-1}$

X = matrix of all points.

For a single predicted value, within 95 percent confidence limits, assuming normality,

$$Y = \hat{Y} \pm t(.025,\ 0.975) \cdot s \sqrt{1 + 1/n + X_o' C X_o}$$

Assuming the Chebyshev inequality, which would hold for any distribution, within the 94 percent confidence limits,

$$Y = \hat{Y} \pm 4 \cdot s \sqrt{1 + 1/n + X_o' C X_o}$$

For the 58-square-mile Walnut Gulch watershed, assuming normality,

$Y = 0.62 \pm 0.11$ c.f.s./acre, or 23,000 ± 4,000 c.f.s.,

and

$Y = 0.62 \pm 0.22$ c.f.s./acre, or 23,000 ± 8,000 c.f.s., assuming the Chebyshev inequality.

Therefore, confidence limits at about the 95 percent level for the predicted maximum expected peak discharge (WG) are at best (19,000, 27,000 c.f.s.) and at the worst (15,000, 31,000 c.f.s.). The first interval represents the best possible conditions with normally distributed errors and the second interval represents the worst possible conditions based on Chebyshev's inequality.

The extrapolated 100-year peak discharge (Fig. 6.5) would be less than 23,000 c.f.s. and, therefore, the possible error less than 8,000 c.f.s. as compared to the range of 100-year peak discharge of 12,000 to 35,000 c.f.s. (plus possible error) assuming various distributions. This is assuming that the error in estimate because of the simplified MLR model is small. Since the correct relationship between rainfall and runoff on Walnut Gulch is unknown this possible source of error cannot be assessed.

If a particular project can be satisfied with the best guess of the maximum expected peak discharge (WG), then the value of 23,000 c.f.s. would be a good figure. If the project demands a more conservative estimate based on the estimated risk, some higher value, possibly based on the 95 percent confidence limits, might be required. However, the extent to which a "conservative" estimate is demanded is a difficult choice. The extent of the loss, and the kind of loss, which could occur will to a large extent determine the conservativeness demanded of the design.

CHAPTER 8

OBSERVATIONS AND DISCUSSION

In Chapters 4 and 5 thunderstorm rainfall-runoff models were developed, based primarily on data from the Walnut Gulch watershed near Tombstone, Arizona. Models based on maximum 30-minute-rainfall (considered the core of runoff-producing thunderstorm rainfall) were correlated with runoff for various sized watersheds within and including the 58-square-mile Walnut Gulch watershed. The results using these models may give reasonable estimates of flood magnitude-frequency for watersheds with similar characteristics between 1 and 100 square miles.

Maximum Peak Discharges

The lack of long term records and the questionable accuracy of some of the data hampered development of recurrence intervals for maximum peak discharges from small watersheds in southeastern Arizona. Most efforts for this region have been to predict peak discharges for intervals up to 50 or 100 years by fitting one of many probability distributions to relatively short records and extrapolating.

For Walnut Gulch the range for the 100-year storm from 6 standard methods was 15,000 to 35,000 c.f.s. (Chapter 2). None of the standard methods shown in Chapter 2 should be used to predict peak discharges for recurrence intervals of more than 100 years without full realization of the uncertainties of the estimate. With only 15 years of record, there is considerable possible error in the 50-year prediction, much less the 100-year flood. Maximum events may be predicted either by assuming a different model for "record" events, or by developing limits on what can be expected under different conditions. The latter method has been used by various persons and agencies to develop models such as the "probable maximum storm" and "maximum possible storm." Such a method was introduced herein with limits placed on wetness of the channels prior to the occurrence of the maximum event. By this method, the maximum expected peak discharge for Walnut Gulch was estimated to be 23,000 c.f.s., which was about the average 100-year storm from the methods shown in Chapter 2, and slightly higher than the 100-year prediction by the log-Pearson Type III method.

In southeastern Arizona, air-mass thunderstorms produce the maximum peak discharges on small (less than 100 square miles) rangeland watersheds, and frontal-convective storms or snowmelt (or a combination of both) produce the maximum peak discharges on large watersheds (over 1,000 square miles). Obviously air-mass thunderstorms produce some runoff from large watersheds, and frontal-convective storms produce some runoff from small watersheds. Therefore, there are two storm populations from which recurrence intervals for peak discharges should be developed. Maximum peak discharges plotted from each population probably intersect someplace between 100 and 1,000 square miles, but the two populations should not be treated as one. However, the two populations are not readily divisible, primarily because the length, accuracy, and diversity of streamflow measurements are inadequate to do so.

Transferability of Rainfall-Runoff Relationships

Thunderstorm rainfall models developed from Walnut Gulch data probably could be applied throughout much of the Southwest, particularly in south central and southeastern Arizona, southwestern and south central New Mexico, and parts of north central Mexico. The Walnut Gulch models should apply as long as air-mass thunderstorms dominate flood producing rainfall in the region. Variation of the maximum expected point rainfall depth from west to east and with elevation in southern Arizona might be a refinement to be considered.

Use of rainfall-runoff relationships from Walnut Gulch on other watersheds is more uncertain. Rainfall-runoff models from Walnut Gulch can probably be transferred with considerable success to similar-sized rangeland watersheds as long as the stream slopes are about the same. The models would be applicable primarily because of the dominance of thunderstorm rainfall over differences in surface infiltration, soils, and geology of the rangeland watersheds. Also, the relatively coarse alluvial channels on Walnut Gulch are typical of rangeland watersheds in much of the Southwest. Rainfall-runoff relationships for Walnut Gulch would not apply for flat cultivated watersheds or for watersheds with physical controls on runoff.

Rainfall-runoff relationships developed for Walnut Gulch may be usable for similar-sized watersheds in the foothills of major mountain ranges and possibly throughout lower mountain ranges. Although both average watershed and channel slopes tend to be greater in the foothills than in the valleys, mountain channels still contain large volumes of alluvial material. The mountain channels also contain flatter reaches that are controlled by rock barriers, which tend to both store and hold back runoff. For example, a maximum peak discharge of 8,500 c.f.s. for 38 years of record was recorded from the 36-square-mile Sabino Creek watershed in the Santa Catalina Mountains in September 1970. This peak, which resulted from a "record" frontal-convective storm, would be about a 10- to 15-year event, according to the runoff relationships developed from Walnut Gulch data.

Rainfall-runoff relationships developed for Walnut Gulch may not hold for timbered watersheds, but there are few records for comparison.

CHAPTER 9

SUMMARY AND CONCLUSIONS

Fifteen years of rainfall and runoff records from a 58-square-mile watershed were used to analyze thunderstorm runoff in southeastern Arizona. Rainfall models were developed, thunderstorm rainfall was correlated to major runoff events, and limits for expected peak discharges were determined.

Summary of Results

Total rainfall from individual thunderstorms in southeastern Arizona represented by isohyetal mapping tends to be elliptical with the long axis about 2 to 3 times that of the short axis. Within the major runoff-producing thunderstorms there is a core of rainfall that tends to be elliptical in shape, with the long axis only 1.5 times that of the short axis. Since volumes and peaks from individual thunderstorms are highly correlated, this core of runoff-producing rainfall can be correlated directly with either the peak or volume of runoff.

The runoff-producing core of thunderstorm rainfall can be approximated for major runoff events from the maximum 30-minute point rainfalls within the runoff-producing area of the watershed. Runoff-producing rainfall lasts for an average of 55 minutes on a 58-square-mile watershed for the major runoff events, but is reduced to a maximum 30-minute rainfall in the model.

The maximum 30-minute rainfall model is applicable on the 58-square-mile watershed because of the nature of thunderstorm rainfall and the characteristics of ephemeral rangeland channels. Runoff-producing rainfall lasts on the average of approximately one hour for the major events on Walnut Gulch. Channel abstractions slow the movement of the flood front over dry channels, with later contributions tending to override the advancing front. Therefore, major flood peaks are the accumulation of discharges from subwatersheds that arrive at about the same time at the watershed outlet, regardless of the direction the storm moves, the shape of the rainfall pattern, or whether the storm lasts for a longer or shorter than average time.

The nature of thunderstorm rainfall controls major peak discharges on the smaller (less than 100 square miles) watersheds, where channel abstractions are outweighed by the runoff-producing core of thunderstorm rainfall.

Because of the nature of thunderstorm rainfall and because the alluvial channels on Walnut Gulch are typical of many rangeland watersheds throughout the region, specific equations that were developed to calculate peak discharges from thunderstorm rainfall for 58- and 8.0-square-mile watersheds should be applicable to similar rangeland watersheds throughout southeastern Arizona. Extrapolations of these equations should also be applicable for similar watersheds from approximately 3 to 100 square miles.

Annual maximum expected peak discharges were determined for Walnut Gulch for 10-, 25-, 50-, and 100-year recurrence intervals from 6 standard statistical methods and the U.S.G.S. graphical method.

Values for the 100-year storm ranged from 15,000 to 35,000 c.f.s. with the suggested government agency method, Log-Pearson Type III, predicting a 100-year peak discharge of 20,000 c.f.s. The Hazen method appeared to fit the data as well or better than the other methods, but none of the methods could be said to best describe the data, and none of the methods could be used to predict peak discharges for longer recurrence intervals with any reasonable degree of accuracy.

Therefore, two limiting curves were developed for expected maximum peak discharge versus watershed drainage, one from Walnut Gulch and other data for southeastern Arizona and the second including data from New Mexico. These curves were designated as the maximum expected occurrences for flood peaks from watersheds of 100 square miles or less. Both curves were based on maximum expected 30-minute thunderstorm rainfall with relatively dry antecedent channel conditions. Rainfall records from Walnut Gulch and other areas in the Southwest indicate that "record" runoff-producing thunderstorms tend to occur on watersheds with relatively dry antecedent channel conditions, because wet antecedent conditions tend to reduce convective heating and thus reduce the potential for a "record" thunderstorm to occur.

Maximum peak discharges from 15 years of record on Walnut Gulch and the maximum expected peak discharges for Walnut Gulch and for the Southwest were compared to flood peaks throughout Arizona. The maximum expected discharge for Walnut Gulch (which should apply for watersheds of about 100 square miles and less) has been exceeded only once (on a 41-square-mile watershed) in Arizona, and that was a miscellaneous measurement near Yuma, over 200 miles west of Walnut Gulch. The maximum curves for peak discharge versus watershed drainage may be useful design curves for watersheds of 100 square miles and less.

Maximum discharges result from frontal-convective storms, and occasionally snowmelt, for watersheds of 1000 square miles and greater. Determinations of maximum expected discharges for small and large watersheds (100 square miles and less as opposed to 1000 square miles and greater) result from different storm systems and should be developed separately. "Steeper" curves for small watersheds that result from air mass thunderstorms and "flatter" curves for large watersheds that result from frontal convective systems, probably intersect between 100 and 1000 square miles.

Assumptions

There were several sets of rather broad assumptions in this paper basic to the development of the rainfall-runoff model. These sets of assumptions are grouped here according to: (1) development of the model for maximum 30-minute rainfall; (2) the applicability of the rainfall model to a rainfall-runoff model; (3) development of the rainfall-runoff model; and (4) use of the model for prediction.

Assumptions in Developing the Rainfall Model

1. The recording rain gage network on Walnut Gulch was dense enough to adequately define air mass thunderstorm rainfall.

2. The individual recording rain gages recorded point thunderstorm rainfall with acceptable precision.

3. Ischyetal maps of individual major thunderstorm rainfall could be "averaged" without distorting the true input beyond acceptable limits.

Assumptions Relating Rainfall to Runoff

1. Thunderstorm rainfall produced the major peak discharges on Walnut Gulch.

2. For major peak discharges, individual cells within the multi-celled thunderstorms occurred so closely together both in time and space that the maximum 30-minute rainfall was an acceptable estimate of the runoff-producing core of rainfall.

3. There was little or no groundwater discharge.

Assumptions in Developing the Rainfall-Runoff Model

1. Multiple linear regression was a suitable means of analysis for thunderstorm rainfall-runoff relationships on a semiarid rangeland watershed.

2. Watershed characteristics that might affect peak discharge could be adequately defined quantitatively.

3. If any of the 8 previous assumptions were both invalid and essential to the relationship, correlations for the regression equations would be poor. In other words, good correlations at least suggested good assumptions.

Assumptions in Using the Model

1. Because of the dominance of intense thunderstorm rainfall, the model is applicable to other rangeland watersheds of similar slope in similar climatic regions.

2. The model can be extrapolated to estimate greater peak discharges than have been recorded as long as there is little out-of-bank flow.

Recommendations for Future Study

Future studies are recommended from records from both existing hydrologic instrumentation on Walnut Gulch and needed new instrumentation in other areas of southeastern Arizona. Hopefully, with more diversified instrumentation, findings from Walnut Gulch could be transferred with greater confidence to other watersheds, or at least compared more quantitatively with data from watersheds throughout the Southwest.

Specifically, future study is recommended to develop stochastic models of both thunderstorm rainfall and runoff; and, as the length and amount of hydrologic data increase, to develop better deterministic models to calculate runoff from thunderstorm rainfall. Further study is also needed to determine the relationships between thunderstorm runoff from watersheds with extreme differences, such as semiarid rangeland versus forested mountain watersheds.

Stochastic Approaches

Stochastic models based on the generally random nature of hydrologic processes (such as the air mass thunderstorms of the Southwest) should be developed. Models predicting peaks and volumes of runoff from individual thunderstorms should be developed from existing Walnut Gulch and other data and continually improved as more data become available. Because of the independent nature of thunderstorms and the relatively minor effect of antecedent channel conditions, such models may be developed solely from runoff and watershed parameters without regard to rainfall. More data probably are needed before annual volumes and annual maximum peak discharges can be predicted successfully with stochastic models, because a 15-year record, such as that on Walnut Gulch, may not include the extremes that are necessary to develop such models.

Most stochastic models of thunderstorm runoff are relatively simple when compared to extremely complex stochastic models for thunderstorm rainfall. Where some stochastic models for thunderstorm runoff have been developed, stochastic models for thunderstorm rainfall are in the development stage. A simplified model, as developed in this paper, can be assigned a rough probability of occurrence of being centered on a particular watershed, and the components that produced this simplified model may be defined well enough to "build" the core of thunderstorm rainfall.

One objective for study would be to develop a stochastic model for thunderstorm rainfall that includes probabilities of being centered on, or intruding onto, watersheds of different shapes and sizes and then calculating resulting runoff by using a deterministic model. The probability of storms of various magnitudes and areal extents occurring within a given region might be based on meteorological conditions.

Deterministic Approaches

There are three principal approaches to hydrologic modeling: (1) constructing a physical model of a watershed and introducing rainfall to this model, (2) representing the watershed by electric analog model, and (3) developing mathematical equations to explain or describe the watershed as an operator on rainfall, from which runoff is calculated by a digital computer. Although physical models are interesting to view and may have some qualitative value, it is doubtful that they will add anything to the knowledge of thunderstorm runoff. However, analog and digital models may be important tools in recreating the extreme variations in thunderstorm rainfall-runoff relationships.

Use of Electric Analogs. A joint project between the Agricultural Research Service and Utah State University to develop an analog model for the Walnut Gulch watershed has been under way for several years. An electric analog was used by Amisial and others (1970) to predict runoff from a 3-square-mile subwatershed of Walnut Gulch. Although the model showed promise, the two storms that were tested were very small (peak discharges of 20 and 30 c.f.s.), and more tests are needed to see if the assumed dominance of the watershed and channel friction factors control the large flows as they appeared to control the very small ones. Possibly, a different, but similar, model may be needed where more emphasis is placed on rainfall intensities and overriding characteristics of channel flows in the relatively steep ephemeral channels on Walnut Gulch.

Use of Digital Computers. Models developed for digital computers, take much the same form as do analog models, at least on paper. The significant parameters are usually the same. Digital models may be faster and more useful than analog models for Walnut Gulch and other semiarid rangeland watersheds, because there are generally no groundwater discharge and return flow components on small semiarid watersheds (100 square miles or less) in southeastern Arizona. The delay or lag features of the electric analog may be best suited to runoff that includes such contributions as snow melt and groundwater discharge, while the rapid movement of thunderstorm runoff overland and through channel system may be better suited to analysis by digital computers.

Channel Abstractions

Better definition of thunderstorm rainfall is essential in developing better models for thunderstorm rainfall-runoff relationships. Also important for developing better models is a better understanding of the flow abstractions in the ephemeral channels. Further study on channel abstractions is essential to developing better rainfall-runoff models for thunderstorm runoff in the Southwest.

SELECTED BIBLIOGRAPHY

Alexander, G. N., A. Karoly, and A. B. Susto. Equivalent distributions with application to rainfall as an upper bound to flood distributions. J. of Hydrology, Vol. 9(3,4), 1969.

Amisial, R. A., J. P. Riley, K. G. Renard, E. K. Israelson. Analog computer solution of the unsteady flow equations and its use in modeling the surface runoff process. Utah State Univ., 1970.

Bell, F. C. Generalized rainfall-duration-frequency relationships. J. of Hydr. Div., ASCE, Vol. 95(HY-1), 1969.

Benson, M. A. Factors affecting the occurrence of floods in the Southwest. U. S. Geological Survey Water Supply Paper 1580-D, 1964.

Benson, M. A. Uniform flood-frequency estimating methods for Federal agencies. Water Resources Research, Vol. 4(5), 1968.

Brancato, G. N. Areal extent of intense rainfall, New Mexico and Arizona. Trans. Am. Geophys. Union Part 4:558-563, 1942.

Chow, Ven Te. Hydrologic determination of waterway areas for designs of drainage structures in small drainage basins. Univ. of Illinois Engr. Exp. Sta. Bul. 462, 1962.

Chow, Ven Te. Handbook of Applied Hydrology. McGraw-Hill Book Co., New York, 1418 pp., 1964.

Court, Arnold. Area-depth rainfall formulas. J. Geophys. Res., 66(6): 1823-1931, 1961.

Dalrymple, Tate. Flood frequency analysis. U. S. Geological Survey Water Supply Paper 1543-H, 90 pp., 1965.

David, F. N., and V. Neyman. Extension of the Markoff theorem on least squares. Statistical Research Memoirs, Vol. II, 1938.

Diskin, M. H., and L. J. Lane. A stochastic model for runoff events for a semiarid watershed in southeastern Arizona. Proceedings Joint ARS-SCS Watershed Modeling Workshop. USDA. March, 1970.

Draper, N. R., and H. Smith. Applied Regression Analysis. John Wiley & Son, 407 pp., 1966.

Fogel, M. M. The effect of the spatial and temporal variations of rainfall on runoff from small semiarid watersheds. Dissertation, Dept. of Watershed Management, Univ. of Arizona, 90 pp., 1968.

Fogel, M. M., and L. Duckstein. Transformation of convective storm patterns into point rainfall frequencies. Water Resources Res. 5(6):1229-1237, 1969.

Grove, G. T. Rillito Creek flood plain study. A report to the City-County Planning Dept., Tucson-Pima County, Arizona, April 1962.

Haltiner, G. J., and F. L. Martin. Dynamical and Physical Meteorology. McGraw-Hill Book Co., New York, 470 pp., 1957.

Harrold, L. L. Discussion of paper entitled "Characteristics of heavy rainfall in New Mexico and Arizona" by L. B. Leopold. Am. Soc. Civ. Engrs. Trans. 109:864, 1944.

Hershfield, D. M. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. U.S. Weather Bureau Tech. Paper 40, 1961a.

Hershfield, D. M. Estimating the probable maximum precipitation, J. of Hydr. Div., ASCE, Vol. 57(HY-5), 1961b.

Hershfield, D. M. Closure-estimating the probable maximum precipitation. J. Hydr. Div., ASCE, Vol. 88(HY-4), 1962.

Hershfield, D. M. Extreme rainfall relationships. J. Hydr. Div., ASCE, Vol. 88(HY-6), 1962.

Hickok, R. B., R. V. Keppel, and B. R. Rafferty. Hydrograph synthesis for small arid land watersheds. Agr. Engr. 40(10):608-611, 615, 1959.

Hickok, R. B., and H. B. Osborn. Some limitations on estimates of infiltration as basis for predicting watershed runoff. Trans. Am. Soc. Agr. Engr. 12(6):798-800, 1969.

Hubbell, D. S., and J. L. Gardner. Effects of diverting sediment-laden runoff from arroyos to range and crop lands. U.S. Dept. of Agr. Tech. Bull. No. 1012, 83 pp., 1950.

Huff, F. A., and G. E. Stout. Area-depth studies for thunderstorm rainfall in Illinois. Trans. Am. Geophys. Union 33:495-498, 1952.

Kent, K. M. A method for estimating volume and rate of runoff in small watersheds. U.S. Dept. of Agriculture, SCS-TP-149, 1968.

Keppel, R. V. A record storm event on the Alamogordo Creek Watershed in eastern New Mexico. J. Geophys. Res. 68(16):4877-4880, 1963.

Keppel, R. V., and K. G. Renard. Transmission losses in ephemeral stream beds. J. Hydraulics Div., Proc. Am. Soc. Civil Engrs. 88(HY-3):59-68, 1962.

Kincaid, D. R., J. L. Gardner, and H. A. Schreiber. Soil and vegetation parameters affecting infiltration under semiarid conditions. Bul. Internatl. Assoc. Sci. Hydrol. 65:440-453, 1964.

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

Kraijenhoff, D. A. Areal distribution of extreme summer rainfalls in the Netherlands. Lecture Tours U.S. Presentation No. 1, August 2, 1963.

Leopold, Luna B. Areal extent of intense rainfalls, New Mexico and Arizona. Trans. Am. Geophys. Union, Part 4, 558-563, 1942.

Leopold, Luna B. Characteristics of heavy rainfall in New Mexico and Arizona. Trans. Am. Soc. Civ. Engrs. 109:837-862, 1944.

Lewis, D. D. Desert floods, a report on southern Arizona floods of September 1962. Arizona State Land Dept., Water Res. Report 13, 1963.

Lieb, H. S. Nature's power plants. Federal Times. June 19, Wash., D.C., p. 28, 1968.

Lindgren, B. W. Statistical Theory. The MacMillan Co., New York, 521 pp., 1968.

Linsley, Ray K. Report on the hydrological problems of the arid and semiarid areas of the United States and Canada. In Reviews of Research on Arid Zone Hydrology. United Nations Educ., Sci., and Cult. Org., 1953.

Linsley, R. K., M. A. Kohler, and J. C. H. Paulhus. Hydrology for Engineers. McGraw-Hill Book Co., New York, 340 pp., 1958.

McDonald, J. E. A critical evaluation of correlation methods in climatology and hydrology. Sci. Report No. 4, Inst. Atmos. Phys., University of Arizona, 1957a.

McDonald, J. E. "It rained everywhere but here"--The thunderstorm encirclement illusion. Weatherwise 12(4):158-160, 174, 1957b.

Mendenhall, W. Introduction to probability and statistics. Wadsworth Publ. Co., 388 pp., 1963.

Miller, J. F., and R. H. Frederick. Normal monthly number of days with precipitation of 0.5, 1.0, 2.0, and 4.0 inches or more in the contiguous United States. U.S. Weather Bureau Tech. Paper 57, 1966.

Minshall, N. E. Predicting storm runoff on small experimental watersheds. J. Hydraulics Div., Proc. Am. Soc. Civ. Engrs. 86 (HY-8):17-38, 1960.

Moran, P. A. P. Statistical treatment of flood flows. Trans. AGU, Vol. 38, 1957.

Nash, J. E., and J. Amorocho. The accuracy of the prediction of floods of high return period. Water Resources Res., Vol. 2(2), 1966.

Ogrosky, H. O. Hydrology of spillway design: small structure--limited data. J. Hydr. Div., ASCE, Vol. 90(HY-3), 1964.

Osborn, H. B. Effect of storm duration on runoff from rangeland watersheds in the semiarid Southwestern United States. Internatl. Assoc. Sci. Hydrol. 9(4):40-47, 1964.

Osborn, H. B. Schematic representation of thunderstorm rainfall. ARS-SCS Watershed Modeling Workshop, Tucson, Arizona, March, 1970.

Osborn, H. B., and L. J. Lane. Precipitation-runoff relationships for very small semiarid rangeland watersheds. Water Resources Res. 5(1):419-425, 1969.

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

Patterson, J. L., and W. P. Somers. Magnitude and frequency of floods in the United States, Part 9. Colorado River Basin, U.S. Geological Water Supply Paper 1683, 1966.

Petterssen, Sverre. Weather Analysis and Forecasting. McGraw-Hill Book Co., New York, Vol. 2, pp. 156-165, 1956.

Raman, V., and M. Baudyopadlya. Frequency analyses of rainfall intensities for Calcutta. J. Sanitary Engr. Div., ASCE, Vol. 95(SA 6), 1969.

Reich, B. M. Annotated bibliography and comments on the estimation of flood peaks from small watersheds. Colorado State Univ., Civ. Engr. Report No. 60, 66 pp., 1960.

Reich, B. M. Design hydrographs for very small watersheds from rainfall. Colorado State Univ. Civ. Engr. Report No. 62, 57 pp., 1962.

Reich, B. M., and L. A. V. Hiemstra. Tacitly maximized small watershed flood estimates. J. Hydr. Div., ASCE, Vol. 91(HY-3), 1965.

Renard, K. G., and R. V. Keppel. Hydrographs of ephemeral streams in the Southwest. J. Hydraulics Div., Am. Soc. Civ. Engrs. 92 (HY-2):33-52, 1966.

Riggs, H. C. Techniques of water-resources investigations of the U.S.G.S.--Some statistical tools in Hydrology. Book 4, Chap. Al, Dept. of Interior, 1968.

Rosenblueth, Arturo, and Norbert Wiener. The role of models in science. Philosophy of Science XII, No. 4, pp. 316-321, Oct., 1945.

Sangal, B. P., and Asit K. Biswas. The 3-parameter lognormal distribution and its application to hydrology. Water Resources Res., Vol. 6(2), 1970.

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

Schuleen, E. P. Discussion of a paper entitled "Characteristics of heavy rainfall in New Mexico and Arizona" by L. B. Leopold, Trans. Am. Soc. Civ. Engrs. 109:864, 1944.

Sellers, W. D. The climate of Arizona. In Arizona Climate by C. R. Greene and W. D. Sellers, Univ. of Arizona Press, pp. 5-64, 1960.

Showalter, A. K. Discussion of a paper entitled "Characteristics of heavy rainfall in New Mexico and Arizona" by L. B. Leopold, Trans. Am. Soc. Civ. Engrs. 109:865, 1944.

U.S. Department of Agriculture, Soil Conservation Service. Methods of flow frequency analysis. Subcommittee on Hydrology, Bull. 13, 1966.

U.S. Water Resources Council. A uniform technique for determining flood flow frequencies. U.S. Water Resources Council, Hydrology Committee, Bull. 15, 1967.

U.S. Weather Bureau. The Thunderstorm. Report of the thunderstorm project. U.S. Department of Commerce, Washington, D.C., 287 pp., 1949.

U.S. Weather Bureau. Generalized estimates of probable maximum precipitation for the United States west of the 105th meridian. U.S. Weather Bureau Tech. Paper 38, 1960.

Wilson, W. T. Discussion--Misconceptions in hydrology and their consequences by V. Yevjevich. Water Resources Res., Vol. 4(5), 1968.

Wisler, C. O., and E. F. Brater. Hydrology. John Wiley and Sons, Inc., pp. 286-300, 1959.

Woolhiser, D. A. Deterministic approach to watershed modeling. ARS and SCS Watershed Modeling Workshop, Tucson, Arizona, March 1970.

Woolhiser, D. A., and H. A. Schwalen. Area-depth frequency relations for thunderstorm rainfall in southern Arizona. Univ. of Arizona Agr. Exp. Sta. Tech. Paper 527, 7 pp., 1959.

Workman, E. J. The problem of weather modification, Science, 138:3538, October 19, 1962.

Yen, Ben Chie. Risks in hydrologic design of engineering projects. J. Hydr. Div., ASCE, Vol. 96(HY-4), 1970.

Yevjevich, V. M. Misconceptions in hydrology and their consequences. Water Resources Res., Vol. 4(2), 1968.