Depth-Area Relationships for Thunderstorm Rainfall in Southeastern Arizona

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RAINFALL statistics from 34 thunderstorms on the Walnut Gulch Experimental watershed in Southeastern Arizona have provided data for determining a convective storm model. Three other thunderstorm rainfall models are compared with that developed from the Walnut Gulch data. Depth-area curves, which should be valuable for design floods, are compared for maximum point rainfalls of 2.0 and 4.2 in. Results suggest that air-mass thunderstorm rainfall should be analyzed separately from frontal and frontal-convective rainfall and that models of thunderstorm rainfall should be separated into more than one category.

Depth-area rainfall relationships are of continuing interest to hydrologists and engineers, particularly in the Southwest where nearly all surface runoff from small arid and semiarid rangeland drainage areas (100 sq miles and less) occurs from high-intensity thunderstorm rainfall. Woolhiser and Schwalen (1959), Osborn and Reynolds (1963), and Fogel and Duckstein (1969) have used depth-area curves developed from limited data to describe thunderstorm rainfall in the Southwest. To develop their models, Woolhiser and Schwalen used 3 years of record from the Atterbury Watershed near Tucson, and Osborn and Reynolds used one exceptional storm from the Alamogordo Creek watershed in northeastern New Mexico. Fogel and Duckstein assumed a bivariate Gaussian distribution proposed by Court (1961) and used 12 years of Atterbury data plus fragmentary information from other sections of the United States to fit this distribution. Court (1961), and Osborn and Reynolds (1963) pointed out that the extreme variability of thunderstorm rainfall both in time and space and the scarcity of data have made quantitative description difficult. In this paper, data from a dense network of recording rain gages in southeastern Arizona are used to describe, quantitatively, thunderstorm rainfall with depth-area equations, and these equations are compared to those from the earlier models.

EXPERIMENTAL WATERSHED

The Southwest Watershed Research Center of the Agricultural Research Service collects data from the 58-sq-mile Walnut Gulch Experimental Watershed located in southeastern Arizona (Fig. 1). Renard (1970) and others have described the hydrology and instrumentation of this rangeland watershed. Cover is dominated by grass in the upper one-third, and by brush in the lower two-thirds. The small city of Tombstone (pop. 1200) lies within the watershed boundary and provides the only significant deviation from grazed rangeland. Rainfall is measured with a network of 97 recording gages. This network is by far the largest and most compact network of recording rain gages in the Southwest. The analyses in this paper are based on 80 of these gages which are fairly evenly distributed on or adjacent to the watershed and which have been in continuous operation for at least 10 years (Fig. 1). The gages that are adjacent to the watershed boundary add to the area covered so that the 80-gage network represents about 70 sq miles.

SEASONAL PRECIPITATION

Sellers (1960), Osborn and Hickok (1968), and others have discussed seasonal precipitation patterns in southern Arizona. In the summer, when moist air flows into the region from the Gulf of Mexico, air-mass thunderstorms occur. These storms produce high-intensity rains of limited aeral extent, and usually occur in the late afternoons or early evenings. Osborn and Hickok (1968) pointed out that almost all runoff from small rangeland watersheds (100 sq miles and less) in the semiarid and arid portions of the Southwest results from thunderstorm rainfall.

In the winter, moist air is associated with generally weak frontal storms moving eastward from the Pacific Ocean. By the time these storms have passed over westerly-lying mountain ranges in southern Arizona, the moisture aloft has decreased so much that usually very little rain or snow results. Although runoff may occur, more often the storms bring only scattered cloudiness to southern Arizona. Occasionally, in the late summer or early fall, heavy rains result from tropical storms off Baja California pushing moist air into southern Arizona. These storms cover larger areas than do the more common air-mass thunderstorms and produce maximum peaks and volumes of runoff from large rangeland watersheds (about 1,000 sq miles and larger) in southern Arizona (Osborn, 1971).

DEPTH-AREA RELATIONSHIPS

Depth-area relationships of 34 air-mass thunderstorms with maximum

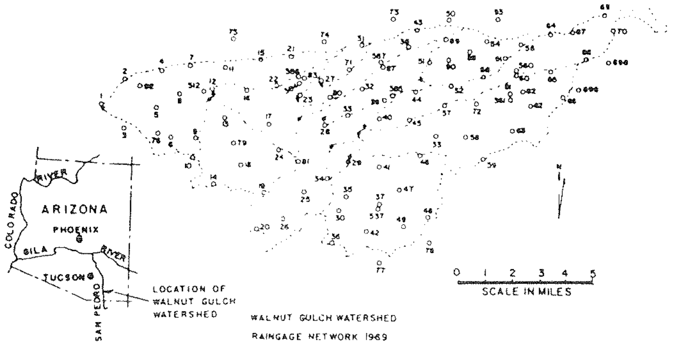

FIG. 1 The Walnut Gulch watershed and location of recording rain gages.

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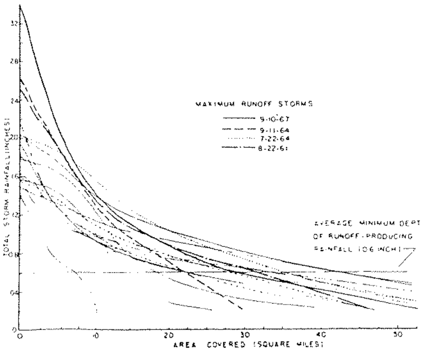

FIG. 2 Depth-area curves for the 16 largest runoff-producing stroms on Walnut Gulch.

sampled point rainfall centered well within the Walnut Gulch watershed were compared in this study. The individual storms consisted of up to six or seven cells closely spaced in time and area. Depth-area curves for 16 of the largest runoff-producing storms are compared in Fig. 2, with the four largest specifically identified. Maximum storm rainfall for the 16 events ranged from 1.4 to 3.45 in. All 16 storms lasted less than two hours, with all runoff-producing rainfall in each storm lasting less than 90 minutes. At any one point within each storm, runoff-producing rainfall (0.6 iph or greater intensity) lasted less than 45 minutes. Other similarities were that rain depths decreased rapidly with increasing area. For the storms with the greatest center depths, the depths generally decreased more rapidly with increasing area than those with lesser center depth.

A reasonably good threshold for runoff occurrence from thunderstorm rainfall on watersheds of one sq mile or larger in southeastern Arizona is 0.6 in. of rain. Using this as a basis for comparison, the storm with the greatest center depth, 3.45 in. covered approximately 32 sq miles with runoff-producing rainfall. In comparison, two storms with center depths of 1.5 and 2.0 in., covered approximately 45 sq miles with runoff-producing rainfall. In the first case, runoff-producing rainfall covered about 45 percent of the 70-mile area represented by the gage network and in the second cases about 65 percent. There was some overlap for lower rain depths from all three storms onto adjacent ungaged watersheds which had to be estimated, but this overlap was probably small. None of the 34 storms was completely contained within the rain gage network, but the 60-sq-mile network was sufficiently large to define the shape of the runoff-producing portions. The runoff-producing portions of the storms were generally elliptical, but there was considerable variation between events.

A preliminary estimate was made of an upper limit enveloping all of the depth-area curves from the 16 largest air-mass thunderstorms recorded on Walnut Gulch. This estimate is shown in Fig. 3 in relation to depth-area curves derived from the 16 largest storms.

The storms shown in Fig. 2 were grouped according to center depth and then averaged to provide the middle two lines shown in Fig. 3. The bottom line in Fig. 3 is an average of the 18 storms with the least center depths (not shown in Fig. 2). Obviously, there is considerable variability in the estimates, but the curves in Fig. 3 do indicate a general decrease in the ratio of areal extent extent to depth for the more intense storms. The range in depths for the four highest storms in Fig. 3 are shown to indicate the variability in the model.

WALNUT GULCH MODEL

A mathematical model was developed to relate storm center depth to areal extent of thunderstorm rainfall. The basic criteria upon which the model is based are that the depth of rainfall covering one sq mile is 90 percent of the maximum point rainfall, that the rainfall depth decreases logarithmically with increasing area covered, and that the areal extent of air-mass thunderstorm rainfall is finite. The model for depth of rainfall covering a certain area is

$$D = D_o\,(0.9 - 0.2 \ln A) \quad . \; . \; . \; . \; . \; [1]$$

where

D = depth of rainfall in inches,

D_o = depth of rainfall at storm center,

ln = natural logarithm (base e),

and

A = area covered by D and greater rainfall, in sq miles, where $1.0 \leqslant A \leqslant 90$.

Court (1961) pointed out that it is difficult to satisfy all requirements for such models in one equation. In this paper, as indicated in equation [1], a logarithmic form was used with emphasis on measured areal extent rather than maximum center depths. For practical use, an estimate of rainfall for one sq mile as a maximum expected value may be all that is needed. However, maximum expected point rainfall was estimated as the next step in the development of the model for air-mass thunderstorm rainfall in southeastern Arizona.

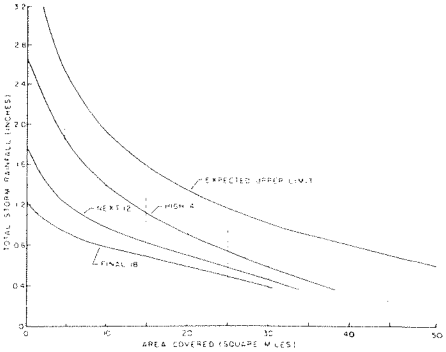

FIG. 3 Average depth-area curves, storms grouped by center depth, for 34 air-mass thunderstorms on Walnut Gulch.

It was noted earlier that the maximum recorded point rainfall for an air-mass thunderstorm on Walnut Gulch was 3.45 in. on September 10, 1967. In that storm, there was about a 10 percent decrease in rainfall covering one sq mile. Adding 10 percent to the upper valid limit of 3.8 in. suggested in Fig. 3 indicates maximum point rainfall of about 4.2 in. Assuming an average 10 percent difference between points about one mile apart for maximum values for runoff-producing thunderstorms agrees with findings by Osborn, Lane, and Hundley (1969) for runoff-producing thunderstorms on Walnut Gulch.

A thorough search of all recording rain gage records in southern Arizona (including approximately 1,000 gage-years of U. S. Weather Bureau records) and a review of standard gage records (including about 2,800 gage-years of USWB records) suggests that an expected maximum of four in. is a reasonable estimate for air-mass thunderstorms in southern Arizona. It must be emphasized that this value is an estimate for an upper limit for short-duration (about two hr or less) thunderstorms, and is not meant to be an estimate for events such as the occasional "September" storm that Sellers (1960) describes as "rampaging through southern Arizona". As stated earlier, these "September" storms produce maximum runoff from large watersheds, but the short duration air-mass thunderstorms produce the peak discharges from small (100 sq miles or less) watersheds. No recording rain gage station in southern Arizona has recorded more than four in. of rainfall in less than two hr from any type of storm in southern Arizona. Again, the greatest measured point rainfall from an air-mass thunderstorm in southern Arizona was 3.45 in. on September 10, 1967 on Walnut Gulch.

A search of rain gage records in New Mexico, as well as Arizona, suggests that about 4.2 in. may be a reasonable estimate for maximum short-duration

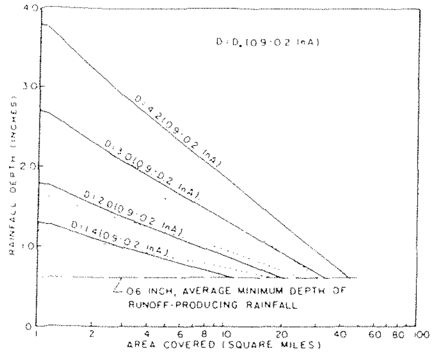

FIG. 4 Depth-area curves for Walnut Gulch, with varying depth at storm center.

thunderstorm rainfall throughout the Southwest. Keppel (1963) reported that just over four in. of rainfall in less than two hr was recorded in northeastern New Mexico from a frontal-convective event on June 5, 1960. For both this event and all of the 34 storms used in the analysis of thunderstorm rainfall on Walnut Gulch, the runoff-producing portion of the rainfall on the watershed was less than 90 minutes. A search of rainfall records in New Mexico failed to reveal any other recorded short duration rainfall approaching four in.

Therefore, 4.2 in. seemed to be a reasonable estimate for maximum expected point rainfall for air-mass thunderstorms in southeastern Arizona. Obviously, there is nothing "absolute" about this limit. It is simply a reasonable estimate based on what has occurred and is known about air-mass thunderstorms in the Southwest. Also, as will be discussed later, the question of frequency of such an event is important in developing depth-area curves for design purposes in the Southwest.

A family of curves based on the grouped events in Fig. 3 and equation [1] were calculated and drawn in Fig. 4. Maximum one-sq-mile rainfall depths of 3.8, 2.7, 1.8, and 1.3 in. were used, respectively, for the equations. The four curves are plotted on semilog paper for easier visual interpretation.

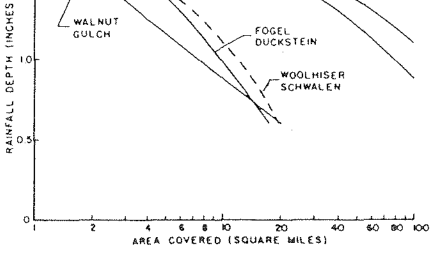

FIG. 5 Depth-area curves for a storm center depth of 2.0 in.

The dotted lines are curves from Fig. 3. The lower two curves in Fig. 4 do not fit the data from Fig. 3 as well as the upper two curves. However, actual data suggest that thunderstorms with lesser center depths also cover finite areas, although estimates of depth-area-relationships below about 0.6 in. are based on extremely large variability between events. Some very brief events with maximum depths of less than 1.4 in. may cover only a few sq miles, while others may cover up to 80 or 90 sq miles. For design purposes for small arid land watersheds, the rather "hazy" depth-area relationships below 0.6 in. or so normally are not critical, since almost all thunderstorm runoff results from rainfall of more than 0.6 in., and most thunderstorm runoff results from storms recording more than 1.0 in. depths of rainfall.

FREQUENCY OPINIONS

For runoff design purposes, a frequency must be assigned to the different maximum point depths. As stated, the estimated maximum expected point rainfall from a single air-mass thunderstorm in southeastern Arizona, determined from point rainfall records, was 4.2 in. Individual consulting engineers and hydrologists might have their own opinion on such a maximum, based on the risk for their particular project.

The design frequency actually refers to a point measurement within a watershed area. For Walnut Gulch, maximum values of point rainfall were determined from 16 years of record. The actual recurrence interval for a point rainfall of 3.45 in. in one storm within the watershed area is unknown, but long-term point records from scattered stations in Arizona at which such a maximum has never been recorded suggest that the interval must be longer than 16 years. Walnut Gulch records suggest that rain of about 2.6 in. center depth might be expected on the 58-sq-mile watershed once in four or five years, and the maximum expected point rainfall within the watershed boundary in any one year is about 2.0 in.

COMPARISON WITH OTHER MODELS

Woolhiser and Schwalen (1959) and Fogel and Duckstein (1969) developed thunderstorm rainfall models based on data from the 29-gage network on the 20-sq-mile Atterbury Watershed near Tucson, Arizona. Woolhiser and Schwalen based their model on three years of record, pointing out that the maximum event was about 2.5 in. at the center. Fogel and Duckstein (1969) assumed a Gaussian distribution as suggested by Court (1961) and developed their model from 12 years of record on the same watershed with two maximum events of about 2.5 in.

The U. S. Weather Bureau, in a report prepared for the U. S. Army Corps of Engineers (1968), presented depth-area-duration curves for probable maximum precipitation in the Southwest. The curves were based primarily on estimates from several storms in California, Nevada, and Utah. In this analysis mathematical functions were fit to these curves for areas less than 100 sq miles.

The equations, including the Walnut Gulch model, are summarized below in similar notations.

$$\text{Walnut Gulch: } D = D_o\,(0.9 - 0.2 \ln A),\ 1.0 \leqslant A \leqslant 90 \;\ldots\; [1]$$

$$\text{Fogel-Duckstein: } D = D_o\, e^{-Ab} \;\ldots\ldots\ldots\ldots\; [2]$$

$$\text{where } b = 0.27\, e^{-0.67 D_o}$$

$$\text{Woolhiser-Schwalen: } D = D_o - 10^{(1/1.57)} \log_{10} A$$

$$- 1.08/1.57) \;\ldots\ldots\ldots\; [3]$$

$$\text{USWB, 3-HR: } D = D_o\,(1 - \sqrt{\frac{A}{0.051}}\,/100),\ 1.0 \leqslant A \leqslant 90$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; [4a]$$

$$\text{USWB, 1-HR: } D = D_o\,(1 - \sqrt{\frac{A}{0.032}}\,/100),\ 1.0 \leqslant A \leqslant 90$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; [4b]$$

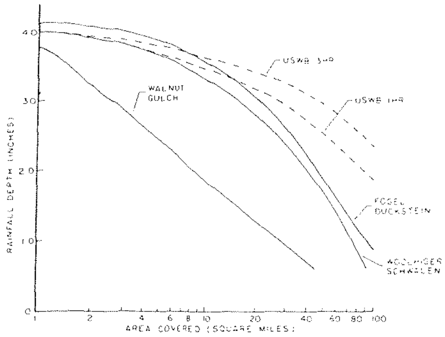

FIG. 6 Depth-area for a storm center depth of 4.2 in.

The five curves were compared for center depths of 2.0 and 4.2 in. (Figs. 5 and 6). As stated earlier, a two-in. point rainfall would be expected on a watershed such as Walnut Gulch on an average of once a year, and a 4.2-in. rain is the expected maximum point rainfall for Walnut Gulch.

For two-in. center depths, the three Arizona curves plot fairly close together, although the Walnut Gulch curve suggests significantly less rainfall volume than the other two. For 4.2-in. center depths, the Walnut Gulch curve indicates less volume than the other four curves with the U. S. Weather Bureau curves plotting the highest. In Fig. 7, the two largest recorded thunderstorm rains on Walnut Gulch (1955-1970), September 10, 1967 and the "record" Walnut Gulch storm, August 17, 1957 (not included in the 34 storms for the depth-area rainfall but for which good records were available) also were included to test the validity of the Walnut Gulch limiting curve. The 1957 storm comes fairly close to the envelope curve but does not cross it, while the 1967 storm almost parallels the envelope curve. Obviously, the Walnut Gulch data suggest different depth-area relationships than do the other three models.

The explanations for the differences between the various models are extremely important because the differences in depth-area relationships are large enough to suggest huge differences in peaks and volumes of runoff, depending on which model is used.

Fogel and Duckstein (1969) tested their model by comparing it with depth-area curves from an exceptional frontal-convective event in northeastern New Mexico on the Alamogordo Creek watershed and reported a good fit. However, Keppel (1963) and Osborn and Reynolds (1963) reported that several events on Alamogordo Creek far exceeded anything recorded during the same period on Walnut Gulch. They concluded that more moisture and greater frontal activity on Alamogordo Creek were responsible for the differences. Since 1963 there have been several exceptional events on Alamogordo Creek that also have far exceeded anything recorded on Walnut Gulch. In turn, for approximately the same period of record, 1957 to the present, there have been several storms on Walnut Gulch that recorded significantly higher amounts of rainfall than have been recorded on the Atterbury Watershed. Yet, the "record" events on Walnut Gulch, which are very well defined, do not fit the Tucson model (Fig. 5), in that they yield far less depth per area for the type of storm exhibited. Certain major frontal-convective events on Alamogordo Creek also do not fit the Walnut Gulch model. However, other runoff-producing events on Alamogordo Creek do fit the Walnut Gulch model, which suggests that there are at least two populations of runoff-producing thunderstorms in northeastern New Mexico––those connected with frontal events and those which are pure air-mass thunderstorms.

The key to the differences is regional and local meteorological variations. Woolhiser and Schwalen (1959) had an admittedly small sample which included storms of longer duration as well as air-mass thunderstorms. Fogel and Duckstein (1969) attempted to fit data from different regions as well as storm types into a universal thunderstorm rainfall model. They used data from northeastern New Mexico in their model, yet, no thunderstorms of the high intensity and related areal extent of those recorded in northeastern New Mexico have been recorded in southeastern Arizona. That is not to say that they could not occur, but that the liklihoods are much, much less. For engineering design, the frequency of magnitude and storm duration are extremely important. If the engineer is faced with runoff design for a small watershed in southern Arizona in which he must be extremely conservative and allow for the maximum that could possibly happen under any circumstances, he might use the U.S. Weather Bureau model as an upper limit. If a more reasonable estimate is desired, based on what has occurred and is more likely to occur within the normal atmospheric and topographic conditions in southeastern Arizona, then he could use the Walnut Gulch model.

OBSERVATIONS

Obviously, the curves in Fig. 4, although a design tool, are not meant to represent rainfall from individual thunderstorms. Differences between events, as illustrated in Fig. 2, should be kept in mind. Also, the question of frequency on smaller or larger watersheds is an added problem. The return interval for a 3.45-in. rain lengthens with decreasing area, probably at about equal ratio to the ratio of the areas. For example, if the 15-year storm on the 58-sq-mile Walnut Gulch watershed is 3.45 in., for a 25- to 30-sq-mile watershed, the same point rainfall might be expected about once every 30 years. Furthermore, although the storm, if centered, could produce a higher peak rate of runoff per unit area than on the larger watershed, there is less chance of the storm being centered on the smaller watershed.

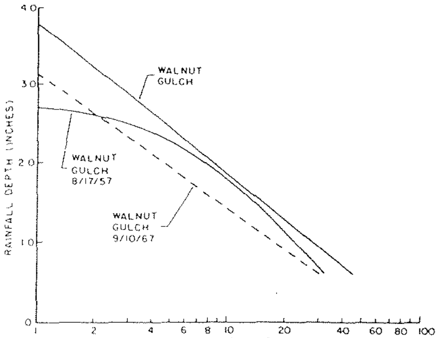

FIG. 7 Comparison of two largest runoff-producing Walnut Gulch storms and the Walnut Gulch envelope design curve.

Estimates of depth-area rainfall for southeastern Arizona are the first "Half" of the problem. However, the information provided in this paper should be of considerable interest and value to the hydrologist and engineer in estimating runoff from semiarid rangelands in the Southwest where the runoff is dominated by air-mass thunderstorms.

CONCLUSIONS

The following conclusions refer to air-mass thunderstorms in southeastern Arizona:

1 None of three other models tested (USWB, Woolhiser-Schwalen, or Fogel-Duckstein) adequately fits the depth-area data from Walnut Gulch.

2 A general equation for depth-area relationship for air-mass thunderstorm rainfall on Walnut Gulch is

$$D = D_o (0.9 - 0.2 \ln A),$$

where

$D =$ total storm rainfall in inches,
$D_o =$ depth of rainfall at storm center,
$A =$ area covered in square miles, with $1 \leq A \leq 90$.

3 To adequately define the shape of runoff-producing rainfall ($D > 0.6$ in.),

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the areal extent of the rain gage network should be at least 60 to 70 sq miles for network-centered storms.

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