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Effect of Storm Rainfall Variability on Runoff From Small Semiarid Watersheds

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RUNOFF is a complicated process under any circumstance. The complexity is increased when causative factors are variable in time and space. That is the situation which exists in southwestern United States during the summer months when most of the annual runoff occurs as a result of convective storm activity. These localized, high-intensity, short-duration storms produce record runoff events on small watersheds. Detailed investigations concerned with the design of hydraulic structures that would be affected by such storms are usually not warranted. A procedure is required, therefore, which allows the designer to estimate the magnitude and frequency of surface runoff from the highly variable convective storm.

Purpose and Scope of Study

As stated by Nash (5)*, the relation between storm runoff and rainfall may be considered in three parts:

1. Relation between volume of storm rainfall and resulting storm runoff volume,
2. Manner in which the storm runoff is distributed in time, and
3. Relation between rainfall frequency and runoff frequency.

Only the first and third parts will be dealt with in this paper.

Since rainfall records are generally available for much longer periods of time than are runoff records, it seems feasible to develop rainfall-runoff relationships in order to use the frequency distributions of existing precipitation records. The usefulness of such a relationship is contingent on the adequacy of frequency distributions of rainfall amounts or intensities. In a previous study, Fogel and Duckstein (2) developed a procedure for determining convective rainfall frequencies using data from a network of rain gages. The authors believe that these results may be more reliable than the conventional methods of establishing point rainfall-frequency distributions.

A widely accepted method for estimating runoff volume is the one developed by the U. S. Soil Conservation Service (8). This procedure, however, does not take into account the difference between the characteristics (intensity, duration, areal extent and frequency) of convective storms and the rainfall resulting from other storm types.

It is the purpose of this paper to present a rainfall-runoff relationship for convective storms and to examine the relation between rainfall frequency and runoff frequency.

Experimental Area

The analysis of 13 years of rainfall and runoff data collected on the Atterbury experimental watershed formed the basis for this study. Located approximately 10 miles southeast of Tucson, Ariz., the watershed is representative of valley floors in southern Arizona. The land slopes range from zero to 5 percent while the subwatersheds are long and narrow and have relatively flat channel slopes. The desert vegetation is primarily creosote bush, cacti and mesquite. The soils range from sandy or gravelly surfaces on the rounded gently sloping ridges to soils with loam surfaces in the nearly level drainageways that separate the ridges. Much of the area is underlaid with a cemented zone of lime accumulation 6 to 24 in. below the surface. The main drainageways consist of either broad, grassy swales or gullies that have sandy bottoms and are as deep as 5 ft and as wide as 20 ft.

As shown in Fig. 1, the research area is drained by two ephemeral streams, Main Wash and Davis-Monthan Wash. The latter is an artificial channel formed by a levee built to prevent flooding to the west. Both washes drain into the main reservoir which has a capacity of 65 acre-ft up to the spillway level. In the upper reaches of the watershed, there are two smaller reservoirs or tanks with capacities of 15 and 7 acre-

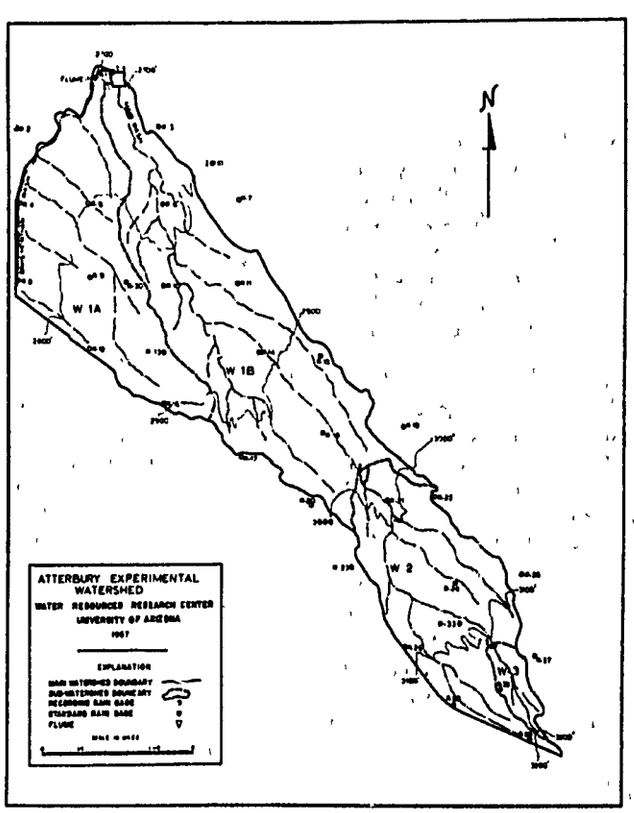

Fig. 1 The Atterbury experimental watershed

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* Numbers in parentheses refer to the appended references.

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TABLE 1. PHYSICAL FEATURES OF ATTERBURY EXPERIMENTAL WATERSHED

Physical feature	Subwatershed W-1A	W-1B	W-2	W-3
Area, square miles	5.17	7.77	4.49	0.47
Average landslope, percent	1.2	2.1	2.6	3.7
Channel slope, percent	0.63	0.82	0.84	1.20
Channel length, thousand feet	32	34	25	10

ft. The experimental area is thus divided into four subwatersheds, the physical features of which are shown in Table 1.

The original basic rain-gage network area of nearly 20 sq miles contains 29 gages laid out on approximately a one-mile grid. Storm runoff volumes are determined from three volumetrically calibrated reservoirs and by use of a critical-depth flume.

Slightly more than half of the annual rainfall of 11 in. falls during the summer months when convective storms are prevalent. Annual runoff averages only 2.5 percent of the annual rainfall with 80 percent occurring during the summer months.

Rainfall Model

While it is not the intent of this paper to discuss the development of the convective storm rainfall model, mention of some of the model's characteristics is deemed necessary prior to discussing the rainfall-runoff relationship.

Spatial Distribution

The depth of localized convective storm rainfall is known to vary from point to point. An area-depth formula is an attempt to describe this spatial variation. The analysis of Atterbury experimental watershed rainfall data resulted in selecting as best representing this distribution the exponential relationship

$$R = R_0 \exp(-bA) \quad [1]$$

where R is the depth of rainfall of the enclosing isohyet, R_0 is the storm center [illegible], A is the enclosed area and b is a dispersion parameter determined to be dependent on R_0. A regression analysis with a correlation coefficient of 0.90 produced the equation

$$b = 0.27 \exp(-0.65 R_0) \quad [2]$$

Although the plotted isohyets of the convective storms that hit the experimental area were definitely found to be elliptical, assuming them to be circular introduces only minor errors. Thus with knowledge, either factual or assumed, of the depth of rainfall at the storm center, the rainfall depth at any distance from the point of maximum rainfall can be determined from equations [1] and [2].

Point Rainfall Frequencies

Using the procedure developed by Fogel and Duckstein (2), point convective rainfall frequencies were calculated and compared with an extremal distribution fitted to historical records of a nearby weather bureau station. This station known as Tucson, University of Arizona has been in continuous operation for 74 years and is located about 8 miles from the lower end of the watershed. The results of this comparison are shown in Table 2.

TABLE 2. COMPARISON OF METHODS FOR CALCULATING RETURN PERIODS FOR CONVECTIVE STORM RAINFALL

Return Period, Years	Rainfall, inches: Model	Historical Records
100	4.0	3.1
50	3.5	2.7
25	3.0	2.5
10	2.3	2.0
5	1.8	1.7
2	1.0	1.3

Rainfall-Runoff Relationship

For this study, it was assumed that convective storm runoff is a function of total storm precipitation, the time distribution of the rainfall and the spatial distribution or the location of the storm rainfall with respect to the gaging station on the watershed. To determine the relative importance of these variables, multiple-regression techniques were used. Assuming the linear form of the regression equation, the model for making this determination can be written as

$$Q = B_0 + B_1R = B_2T + B_3S + e \quad [3]$$

where Q is storm runoff, R total storm rainfall, T is a time distribution factor, S is a space factor which indicates where the heaviest rainfall was located on the watershed, B ($i = 0, 1,2,3$) are coefficients to be estimated, and e is the error of estimation.

While antecedent rainfall is usually considered as having a pronounced effect on runoff, the work of Keppel (4) and Schreiber and Kincaid (7) has shown that is not the case when the runoff is associated with convective storms. Subsequent analysis of Atterbury data resulted in a similar conclusion.

Description of Variables

In using multiple-regression techniques, an inherent assumption is that the variables R, T and S are independent among themselves. It is readily apparent that convective storm rainfall and storm-center location on the watershed are independent variables. The relationship between total storm rainfall and the time distribution of rainfall is not as clearly independent. For example, the maximum intensity for a 60-min period correlated very closely with the storm total. There was less correlation using a 30-min period and still less with a 15-min interval. The maximum intensity for a 15-min period was, therefore, selected as being representative of a short burst of runoff-producing rainfall which is sufficiently uncorrelated with the storm total to warrant consideration as being an independent variable.

The time when the maximum 15-min intensity occurs during a storm is also assumed to be an important consideration in determining a time distribution variable. Most convective storms have their high-intensity period during the early stages of the storm. Some storms have low initial intensities which then build up to a maximum. It was assumed that these latter storms should produce more runoff than a storm with an equivalent amount of rainfall in which the peak intensity occurs initially. During the early stages of a storm, the infiltration capacity of the soil is relatively high. If storm intensities are low at this time, all of the rainfall will infiltrate into the soil which tends to reduce subsequent infiltration. Thus, for the period when rainfall rates are high a greater portion will tend to runoff in the case of storms which have their peak intensity sometime after the start of a storm than for storms having their peak rates occurring initially.

The time from the start of rainfall to the mass center of the storm was selected as being related to the occurrence of the short burst of runoff-producing rainfall. In order to have only one time-distribution variable, the maximum 15-min intensity, i_{15}, and the time to mass center, t_m, were combined into the form

$$T = f(i_{15}, t_m) \quad [4]$$

Since there is no rational method for writing the exact function of T, the relationship chosen was

$$T = i_{15}\, t_m^{i} \quad [5]$$

where n has a value between 0 and 1 which denotes the relative importance of the two terms.

The value of n was determined by trial and error. Selecting values for n, a corresponding T was computed with equation [5]. The raingage recording the greatest total for the particular watershed was used in making these calculations. Each value of T was then inserted into the regression equation

$$Q = b_0 + b_1 R + b_2 T \quad [6]$$

where R is the mean storm rainfall for the watershed. The value of n that consistently gave the highest multiple-correlation coefficient for the subwatersheds was selected.

In a similar fashion, the storm's space or location factor S was chosen to describe the positioning of the storm on the watershed. Under consideration as components was the distance from the storm center or point of maximum rainfall to the watershed outlet and the area of the watershed that received at least a specified amount of rainfall. After numerous trials on the four subwatersheds, it was determined that no combination of these components significantly improved the correlation. This was probably due to the relatively small watershed areas used in this study, so that using the mean value for the storm rainfall masked the effect of the storm location factor S. Thus, only two variables which describe rainfall characteristics affecting runoff were used in the final regression equation. These were the mean storm rainfall and a time-distribution factor. The regression equation used to determine the extent of these effects is

$$Q = b_0 + b_1 R + b_2 i_{15} t_m^n \quad [7]$$

Prediction Equations

Table 3 summarizes the results of the regression analysis for three of the four subwatersheds on which data were collected. The fourth watershed, W-1A, was not used since some of the hydrologic characteristics of the area were altered during the period of record.

Three prediction equations were determined for each of the three subwatersheds. For the first group, mean storm rainfall was the only independent variable used. In the second set of equations, a value for the exponent n of 1/3 was used as it consistently gave the highest correlation coefficient. In the search for the simplest time-distribution factor, n was set equal to zero leaving only the maximum 15-min intensity to represent the time distribution factor for the third set of equations.

In the first set of the prediction equations, in which mean storm rainfall was the only independent variable used, the coefficient of determination, r^2, ranged from 61 to 86 percent. The smallest subwatershed, W-3, had the highest correlation. Introducing the compound time-distribution variable into the regression equation significantly reduced the unexplained variance, $1-r^2$, in each case.

Using the maximum 15-min intensity alone as an independent variable was not as effective in reducing the unexplained variance. For the two larger subwatersheds, inclusion of this variable into the regression equation was significant at the one percent level. The significance level for the small watershed was five percent.

In subwatershed W-1B, for example, the prediction equation in which there is only one independent variable is

$$\hat{Q} = -0.0729 + 0.2401\,\bar{R} \quad [8]$$

Rearranging and using equation [8] in a deterministic manner results in

$$Q = 0.24\,(\bar{R} - 0.31) \quad [9]$$

In this form, the term within the parenthesis can be considered as effective rainfall in which the average initial abstractions (I_a) are equal to 0.31 inches. Also, the ratio of the runoff volume to the effective rainfall volume can be defined as a runoff coefficient (C_r) which is 0.24 in this instance. Using these terms, a general rainfall-runoff relationship becomes

$$Q = C_r\,(\bar{R} - I_a) \quad [10]$$

A similar result can be derived from the cumulative functions of infiltration and rainfall. It can be shown that both of these functions can be approximated by power equations in which the variable time is raised to the one-half power (1).

The data shown in Table 3 appear to suggest that there are areal limits for which equations that contain only mean storm rainfall can be used to estimate runoff. As the watershed area increases, the correlation between rainfall volume and runoff volume decreases. For the larger watersheds, it is possible that including some type of storm-location variable will be required to account for the variations in runoff.

TABLE 3. COEFFICIENTS OF REGRESSION AND DETERMINATION FOR RUNOFF PREDICTION EQUATIONS

Prediction Equation	Subwatershed W-1B	W-2	W-3
$\hat{Q} = b_0 + b_1\bar{R}$			
b_0	−0.0729	−0.0505	−0.0934
b_1	0.2401	0.1453	0.2208
r^2	0.61	0.63	0.86
$\hat{Q} = b_0 + b_1\bar{R} + b_2 i_{15} t_m{}^{1/3}$			
b_0	−0.1798	−0.1555	−0.1462
b_1	0.1468	0.1022	0.1588
b_2	0.0891	0.0788	0.0722
r^2	0.75	0.87	0.94
$\hat{Q} = b_0 + b_1\bar{R} + b_2 i_{15}$			
b_0	−0.1593	−0.1801	−0.1402
b_1	0.2123	0.1405	0.1918
b_2	0.0354	0.0406	0.0299
r^2	0.69	0.79	0.89

Comparison of Runoff Formulas

A direct comparison of the prediction equations shown in Table 3 with other methods is difficult because these latter procedures do not require a knowledge of the storm's time distribution. As previously mentioned, a common method for estimating runoff volume from storm precipitation is the one developed and used by the U. S. Soil Conservation Service. This method requires the estimation of a runoff curve number which reflects the hydrologic soil-cover complex of a watershed. The antecedent moisture condition (AMC) is taken into account by modifying the runoff curve number. Even though experimental results in this and other stulies have indicated that antecedent moisture has little or no effect on runoff from convective storms, the amount of runoff estimated by the Soil Conservation Service procedure is greatly affected by the assumed antecendent moisture condition of the watershed.

In an effort to make a comparison of runoff formulas, a runoff curve number for Atterbury Experimental Watershed is estimated using a dry antecedent moisture condition. This results in the equation

$$Q = (R - 0.78)^2/R + 3.11 \quad [11]$$

A dry antecedent moisture condition is estimated when the five-day total antecedent rainfall is less than 1.4 inches. For most semiarid areas, this is better than a 90 percent probability (3).

Using subwatershed W-1B as an example, Fig. 2 compares equation [11] with the simple prediction equation for this particular watershed, equation

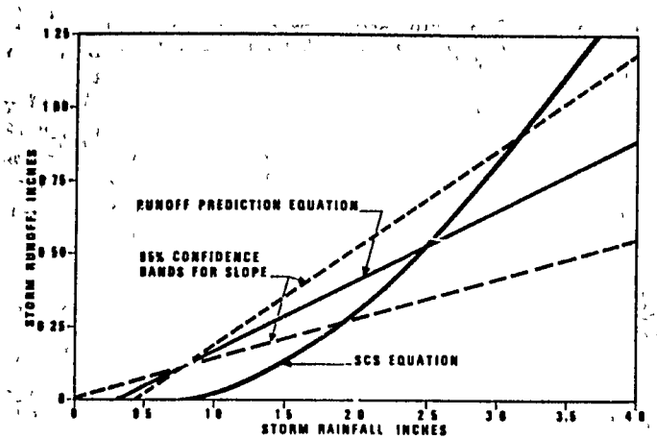

Fig. 2 Rainfall-runoff equations for Watershed W-1B

[8]. Assuming that only the slope of the regression line varies, 95 percent confidence bands are depicted in Fig. 2.

In regression equations, two constraints determine the line. These are the centroidal point $(\bar{x}, \bar{y})$ and either the slope or the intercept. If it is assummed that there is an error in $\bar{y}$, this leads to a constant error in y causing the regression line to be translated up or down without a change in slope. In the physical situation, this implies that whatever is causing the variance in predicting runoff affects only the initial abstractions However, according to the multiple-regression analysis, the storm's time distribution accounts for a significant portion of the variance. Physically it appears more rational to assume that the storm's time distribution affects the ratio of runoff to effective rainfall. With this assumption, therefore, the slope of the line can be used to explain the variance.

From Fig. 2, it is seen that, in comparison with the prediction equation, the SCS procedure underestimates runoff for mean storm rainfall amounts up to about 2.0 in. For small watersheds, this would require a storm center depth of nearly 3.0 in., a once in 25-year event. There is reasonably good agreement for storms of from 2.0 to 3.0 in. as the SCS equation predicts runoff amounts that fall between the 95 percent confidence bands for the prediction equation. A similar situation exists with the other two subwatersheds.

Estimating Runoff

In developing a method for estimating runoff from ungaged watersheds using precipitation records, an inherent assumption is that, with a rainfall-runoff relationship, a similar relation exists between their frequencies of occurrence. In an effort to evaluate the rainfall-runoff relationship, runoff frequencies were calculated by two separate procedures.

For one method, an annual series of maximum runoff volumes during the summer months was prepared for the 13 years of record. The data were fitted to a Type 1 extreme-value distribution using techniques proposed by the U.S. Geological Survey (6). As shown in Fig. 3, this frequency distribution appears to describe adequately the annual series for subwatershed W-1B. Similar results were obtained with subwatersheds W-2 and W-3. The plotting positions were determined by the Kimball method. Runoff volumes for various return periods were then obtained using the theoretical distributions.

The runoff volumes obtained from their annual series were then compared to values determined from the rainfall-runoff relationship and the previously developed frequency distribution for convective storm rainfall. Point rainfall depths for selected return periods are shown in Table 2. Each of these amounts were assumed to be the maximum depth of rainfall of a convective storm. These storms were then superimposed over the subwatersheds according to the spatial distribution relationship (equations [1] and [2]). The mean storm rainfall was calculated by the isohyetal method. This value was inserted into the simple prediction equation shown in Table 3 from which the expected runoff volume for a given return period was determined.

A comparison of the two methods for estimating runoff volumes for selected return periods is shown in Table 4. This check on the rainfall-runoff relationship indicates that, for the longer return periods, runoff as determined from the annual maximum series is, for all three cases, about 10 percent greater than runoff calculated from the regression equations. It also tends to substantiate the use of the procedure developed by Fogel and Duckstein (2) for calculating point convective rainfall frequencies. Using the rainfall frequencies developed from relatively long-term historical records (Table 2) would result in considerable lower runoff volumes than is obtained from the annual series of maximum runoff volumes.

Summary

Convective storms generally produce the annual peak volumes and rates of runoff from small semiarid watersheds. The characteristics that describe these storms—intensity, duration, areal extent and frequency—are markedly different from other storm types. Current methods for estimating runoff volumes require knowledge only of the total depth of rainfall.

In an effort to determine the relative effects of the storm depth of rainfall, the time distribution of the storm rainfall and the positioning of the storm on the watershed, a linear, multiple-regression model was used It was found that the location of the storm center on the relatively small watersheds has little or no effect on runoff when the mean areal rainfall was used to characterize storm magnitude. It is assumed that, for small watersheds, the storm's mean depth adequately takes

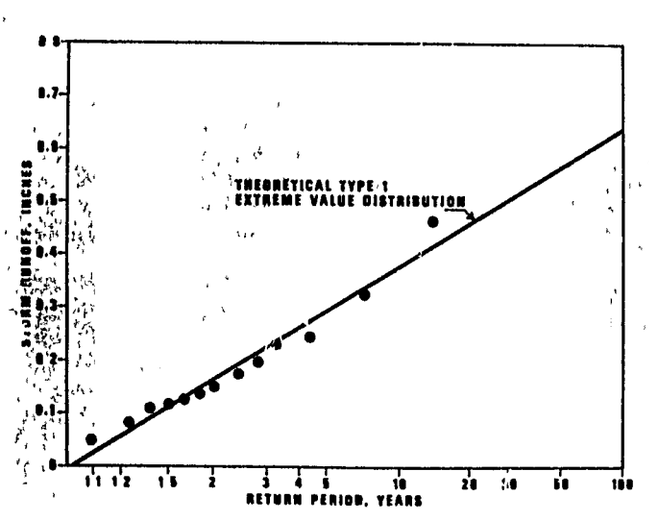

Fig. 3 Frequency distribution for runoff volumes from watershed W-1B

TABLE 4. COMPARISON OF METHODS FOR ESTIMATING RUNOFF VOLUMES FOR SELECTED RETURN PERIODS

Subwatershed	Return period years	Storm center depth, inches	Mean rainfall, inches	Runoff, inches	
				By annual series	By rainfall-runoff equation
W-1B (4974 acres)	100	4.00	2.82	0.62	0.60
	50	3.50	2.42	0.56	0.51
	25	2.96	2.00	0.45	0.41
	10	2.30	1.55	0.36	0.30
	5	1.77	1.04	0.28	0.18
	2	0.95	0.63	0.19	0.08
W-2 (2875 acres)	100	4.00	3.43	0.50	0.46
	50	3.50	2.92	0.44	0.39
	25	2.96	2.47	0.36	0.32
	10	2.30	1.93	0.27	0.24
	5	1.77	1.37	0.20	0.15
	2	0.95	0.72	0.09	0.06
W-3 (302 acres)	100	4.00	3.90	0.84	0.77
	50	3.50	3.40	0.71	0.66
	25	2.96	2.86	0.60	0.54
	10	2.30	2.22	0.44	0.40
	5	1.77	1.70	0.32	0.28
	2	0.95	0.90	0.14	0.11

into account the spatial variations of convective storm rainfall.

While the mean rainfall exerted the major influence in predicting runoff, the distribution of the storm in time was found to add a significant contribution. Two time distribution factors were tested. These were the maximum 15-minute intensity and the time to the mass center of the storm combined with the maximum 15-minute intensity. The use of the combined factor allowed slightly more of the variance to be explained than using the maximum 15-min intensity alone.

When an antecedent rainfall index was used in the linear model with the mean rainfall variable, no significant increase in correlation was obtained. This does not necessarily mean that antecedent soil moisture has no effect on runoff. It may mean that the likelihood of two or more storms occurring on the same area within a short time span is rather remote.

To compare the results of this study with the commonly used U.S. Soil Conservation Service method, the simple regression equation which contains only a mean rainfall term, was used together with confidence bands for the slope of the regression line. In general, the SCS procedure underestimated runoff for most storm rainfall depths and overestimated the volume of runoff for the extreme events.

The Type I extreme-value distribution was found to describe adequately the annual maximum series of runoff volumes. Although the 13 years of record was not deemed to be of sufficient length to firmly establish the use of this distribution, the results did tend to give some credence to the procedure for estimating runoff volumes and frequencies from rainfall data.

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