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Precipitation-Runoff Relations for Very Small Semiarid Rangeland Watersheds

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Abstract. Simple linear regression models for predicting total volume of runoff, peak rate of runoff, duration of runoff, and hydrograph lag-time were developed using three years of data from four small (0.56 to 11.0 acres) watersheds. The models developed indicated that runoff volume was most strongly correlated to total precipitation; that peak rate of runoff was most strongly correlated to the maximum 15-minute depth of precipitation; that flow duration was most strongly correlated to watershed length; and that lag time was most strongly correlated to watershed area. These independent variables accounted for 70, 70, 50, and 30%, respectively, of the variance in the predicted variables. The exponential decay form of the antecedent precipitation equation accounted for 8% of the variation in runoff on one watershed but was insignificant on the others. Analysis indicates that the data represent the high frequency events. It is possible that these models will not accurately predict the low frequency events.

INTRODUCTION

Precipitation and resulting runoff have been studied by the Agricultural Research Service on the Walnut Gulch Experimental Watershed in southeastern Arizona since 1954 (Figure 1). Almost all storm runoff on Walnut Gulch results from short-lived, intense summer thunderstorms of limited areal extent that occur generally in the late afternoon and early evenings in July, August, and the first half of September. About 90% of the annual runoff on Walnut Gulch occurs in July and August [*Osborn and Hickok*, 1968].

In 1954 and 1955 a network of 25 weighing-type recording rain gages was installed on the 57-square-mile watershed. This network was increased to 64 rain gages by 1960 and to 93 recording rain gages by 1967 (Figure 2). Most of the 29 gages added since 1960 were located either outside the watershed boundary or on special intensive study areas. This paper analyzes data from one of these highly instrumented intensive study areas.

Before 1962, the smallest watershed from which runoff was measured was 560 acres. It soon became apparent that on-site runoff and runoff from very small watersheds were much greater per unit area than runoff from the larger complex watersheds. Seventy plots were established on the Walnut Gulch watershed in 1962 and 1963, in an attempt to bridge the gap existing in the knowledge of precipitation-runoff relationships between plots and complex watersheds. Concurrently, six small watersheds in each of two intensive study areas were instrumented, representing vegetative contrasts on Walnut Gulch. The implementations and early observations from these small watersheds, called unit-source watersheds, were described by *Kincaid et al.* [1966].

Schreiber and Kincaid [1967], using data collected from the plots established in 1963, developed regression models for predicting on-site runoff from short-duration convective storms. Using a stepwise multiple linear regression equation, they found that average runoff increased as precipitation increased, decreased as crown spread of vegetation increased, and decreased as antecedent soil moisture increased. The independent variables accounted for 72, 3, and 0.5%, respectively, of the prediction variance. In other words, precipitation completely dominated their correlations. Also, they found that runoff was strongly correlated to the maximum 5-minute intensity of rainfall. The decrease in runoff with increasing soil moisture may be explained by the conditioning of the normally dry surface to allow an increase

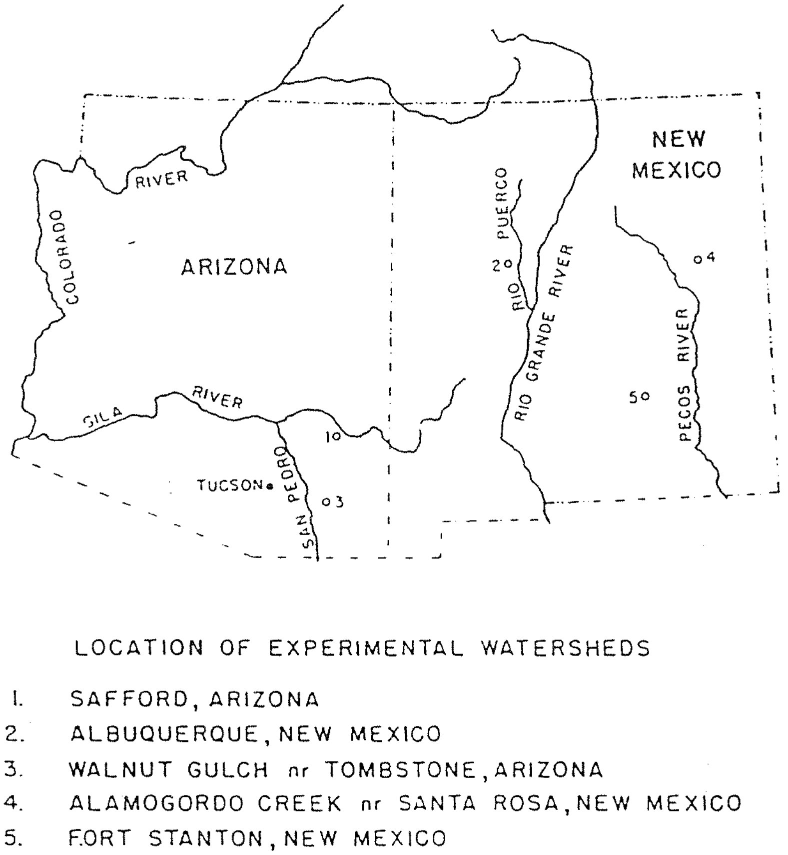

Fig. 1. Location of experimental watersheds.

in the rate of infiltration. *Minshall* [1960] found that runoff was positively correlated to antecedent soil moisture for midwestern watersheds, but Schreiber found that antecedent soil moisture had little effect on runoff, which reinforces observations for southwest rangeland watersheds.

The general equation ($Q = 0.1290 + 0.5036P$) as developed by Schreiber and Kincaid indicates that about 0.26 inch of rain must fall before runoff begins. The threshold value of 0.26 inch of precipitation is found by setting Q equal to zero in the above equation and solving for P. In these plot studies, the volume of runoff from each plot was measured, but not the rates of runoff. Therefore, no comparison could be made between rainfall intensity and peak rate of runoff.

It is the purpose of this paper to expand Schreiber's and Kincaid's efforts to the natural unit-source watersheds on the Walnut Gulch watershed and to determine whether other parameters become more significant with the increase in area and complexity of the rangeland watershed.

PROCEDURE

In 1962, two unit-source areas, one in grassland and one in brushland, were chosen for more intensive study. Four unit-source watersheds (LH-1, LH-2, LH-3, and LH-4) ranging in size from 2.8 to 11.0 acres were established on the brush-covered Lucky Hills Ranch about one mile from Tombstone, and two unit-source watersheds of 4.6 and 120 acres were established on the grass-covered Kendall Ranch on the upper end of the Walnut Gulch watershed (Figure 3). Runoff was determined from continuous records of FW-1 water-level recorders situated above broad-crested V-notch weirs. In the spring of 1965, 3-foot H-flumes were installed

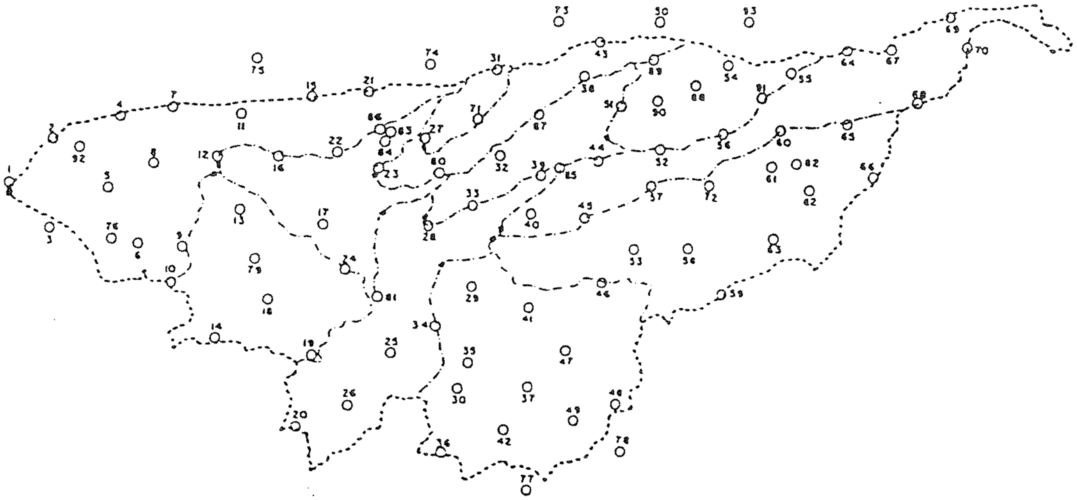

Fig. 2. Walnut Gulch watershed–rain gage network.

at Lucky Hills to measure runoff from ½- and 1-acre unit-source watersheds. There are 3 recording rain gages within the 18-acre Lucky Hills complex (Figure 4).

Storm data for three years (1965 through 1967) from LH-3 (8.3 acres), LH-4 (11.0 acres), LH-5 (0.56 acres), and LH-6 (1.07 acres) were used to develop the precipitation-runoff relationships in this paper. Runoff records at these four stations were good; precipitation records were very good.

Schreiber worked with five independent variables in his plot studies: total storm precipitation, maximum 5-minute intensity, antecedent soil moisture, basal area, and crown spread of vegetation. His dependent variable was storm runoff volume.

Since more output information was available from the unit-source watersheds, the input variables were expanded to include, as well as storm precipitation, maximum depths of precipitation for 5-, 10-, 20-, and 30-minute intervals, and duration of both total storm rainfall and runoff-producing rainfall (Table 1). The five dependent variables were runoff peak rate, total volume of runoff, rise time, lag time, and duration of runoff (Table 1).

We arbitrarily chose two equations [*Linsley et al.*, 1949] for antecedent soil moisture, one based on a reciprocal decay and the other on

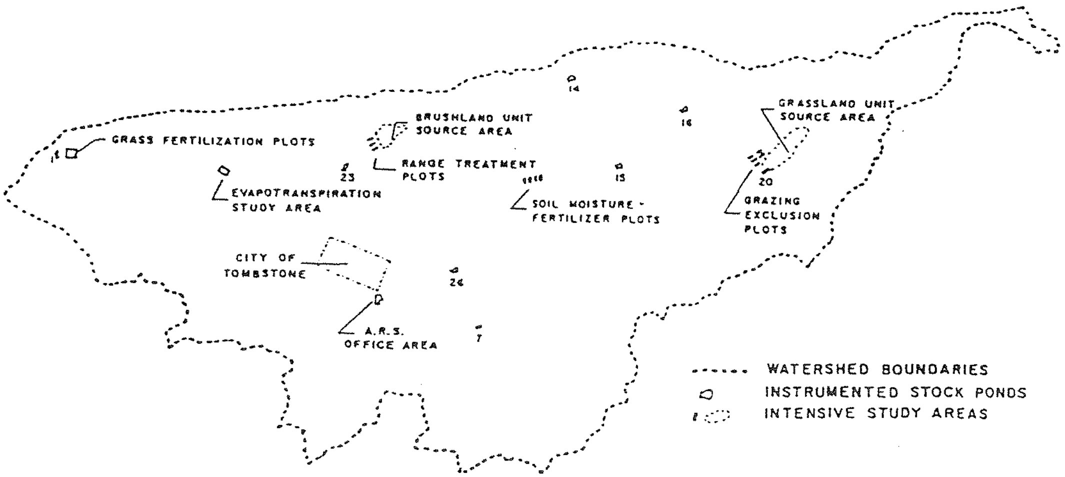

Fig. 3. Intensive study areas on Walnut Gulch Watershed.

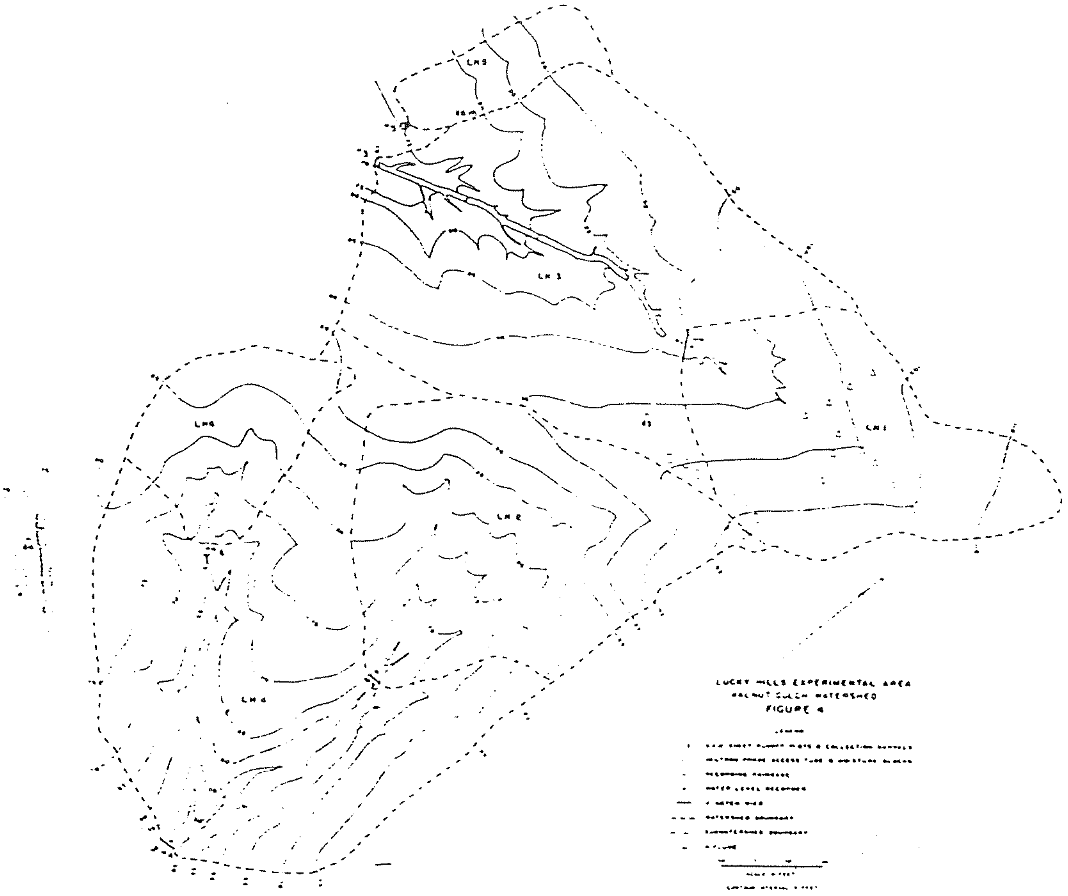

Fig. 4. Lucky Hills experimental area.

an exponential decay (Equations 1 and 2). Time was in hours rather than days.

$$P_{aw} = \sum_{t=1}^{n} 1/tP_t \qquad (1)$$

$$P_{ac} = \sum_{t=1}^{n} P_t K^t \qquad (K = 0.97) \qquad (2)$$

Where P_t is the depth of precipitation in the one-hour interval t hours before the event.

Since the four Lucky Hills watersheds were relatively homogeneous, the small differences in cover were difficult to define, and the two vegetation parameters were dropped from the study. Three watershed parameters were added: watershed area, average watershed slope, and watershed length, making a total of ten precipitation variables, three watershed variables, and five runoff variables (Table 1).

RESULTS

Run No. 1—Correlation of runoff variables for each watershed with independent variables from runoff-producing storms.

Using a stepwise multiple linear regression program (*MLR*), values for the ten independent rainfall variables and five dependent runoff variables for the runoff-producing events were entered into the digital computer. Watershed parameters were not included in the first run. The program selected the most significant input variable for each watershed for each runoff variable according to the simple equation: $Y = ax + b$. The computer automatically selects the next variable in combination with those variables previously included in the regression that will reduce the unexplained var-

TABLE 1. Walnut Gulch, Lucky Hills Watershed *MLR* Program

List of Variables	
P_{tot},	Total volume of precipitation, in.
P_{5},	Maximum 5-minute depth of precipitation, in.
P_{10},	Maximum 10-minute depth of precipitation, in.
P_{15},	Maximum 15-minute depth of precipitation, in.
P_{20},	Maximum 20-minute depth of precipitation, in.
P_{30},	Maximum 30-minute depth of precipitation, in.
P_{aw},	Antecedent Precipitation Index (equation 1) (reciprocal recession), in.
P_{ac},	Antecedent Precipitation Index (equation 2) (exponential recession), in.
D_{pt},	Total duration of rainfall per individual storm, min.
D_{pd},	Duration of runoff-producing precipitation ($i \geq 0.4$ in/hr), min.
A,	Watershed area, acres
S_{a},	Average watershed slope, per cent
L_{max},	Straight line segments length of watershed, ft
Q,	Total volume of runoff, in.
Q_{pr},	Peak rate of runoff, in./hr.
D_{rt},	Total duration of runoff, min.
T_{r},	Rise time (from start of runoff to peak), min.
T_{1},	Lag time (from center of maximum intensity to hydrograph peak), min.

iance the most in a single step. Significance was indicated by the required F level. The degree that each independent variable improved on the mean of the runoff variable was indicated by the value of R^2, the coefficient of determination.

For three of the four watersheds, total precipitation was the principal variable for determining runoff volume (Table 2). On the fourth watershed (LH-5) runoff was strongly correlated to the maximum 20-minute depths of precipitation. Total precipitation accounted for from 76 to 89% of the variance on the four watersheds. On LH-3, LH-4, and LH-6 a second variable added significantly at the 1% level to the prediction equations, but the third variable did not, in any instance, add significantly to the equation (Table 3).

Antecedent precipitation (P_{ac}) accounted for about 8% of the variance on LH-4, and duration of runoff-producing precipitation accounted for about 6% of the variance on LH-3 and LH-6. Only one variable was significant on LH-5.

The maximum depth of rainfall for either 10 or 15 minutes was the principal variable for determining peak rate for three of the four watersheds (Table 2). On LH-5 and LH-6, only the maximum 10-minute depth of rainfall contributed significantly at the 1% level to the prediction equation for peak discharge (Table 3). Again, antecedent precipitation, based on the exponential recession, significantly contributed to the equation for LH-4.

Several conclusions were drawn from this first program. There was a negative correlation on one watershed (LH-4) between runoff and antecedent rainfall (*Pac*). Apparently runoff may decrease with higher values of antecedent moisture, assuming that the antecedent precipitation equations are representative of antecedent soil moisture (Table 3). This condition was noted by Schreiber for one year of record in his plot studies and also by *Hickok and Osborn* [1968].

There was no significant correlation between any of the precipitation variables and duration,

TABLE 2. Variables Determining Q and Q_{pr} for Lucky Hills Unit-Source Watersheds: Entering Order of Variables and Significance

Watershed					
		Variables determining Q			
LH-3	P_{tot}	D_{pd}	P_{10}	D_{pt}	P_{aw}
R^2	$\underline{.89}$	$\underline{.95}$	.96	.96	.97
LH-4	P_{tot}	P_{ac}	D_{pt}	P_{20}	P_{10}
R^2	$\underline{.88}$	$\underline{.96}$	.98*	.98	.99
LH-5	P_{20}	D_{pt}	P_{10}	P_{ac}	P_{30}
R^2	$\underline{.81}$	.82	.84	.84	.85
LH-6	P_{tot}	D_{pd}	D_{pt}	P_{20}	P_{10}
R^2	$\underline{.76}$	$\underline{.83}$	.84	.84	.84
		Variables determining Q_{pr}			
LH-3	P_{15}	D_{pt}	P_{10}	P_{5}	P_{ac}
R^2	$\underline{.88}$	$\underline{.95}$	.96	.97	.97
LH-4	P_{tot}	P_{ac}	D_{pd}	P_{10}	D_{pt}
R^2	$\underline{.84}$	$\underline{.94}$	.97*	.97	.98
LH-5	P_{10}	D_{pd}	P_{tot}	P_{aw}	P_{15}
R^2	$\underline{.85}$	.87*	.90*	.90	.90
LH-6	P_{10}	D_{pt}	D_{pd}	P_{tot}	P_{20}
R^2	$\underline{.76}$	.80*	.82	.84	.86

——— Significant at 1% level.
* Significant at 5% level.

lag time, or rise time of runoff, which probably indicates that other parameters, possibly combined with one or more rainfall variables, determine these runoff variables.

Since only the runoff-producing events were used in this analysis, the runoff equations are biased toward total precipitation. If all events above a certain minimum value were included, a shorter duration of rainfall might become more significant, i.e., P_{tot} might not be the first variable selected by the *MLR* program.

Along with this point was the question of threshold conditions. By using total precipitation as the dominant variable determining runoff, the prediction equations for LH-3, LH-4, and LH-6, respectively ($Q = 0.40\ P_{tot} - 0.10$, $Q = 0.32\ P_{tot} - 0.12$, and $Q = 0.25\ P_{tot} - 0.08$) gave 0.26, 0.38, and 0.32 inch of precipitation necessary before runoff began. The average of 0.32 inch was higher than that found by Schreiber for his plots. This average seemed reasonable, because the retention capacity in the channels of the watersheds was not present in the plots.

Run No. 2—Correlation of runoff variables for all watersheds with independent variables for all significant storms.

Watershed area, average watershed slope, and length of watershed were added to the 10 precipitation variables. Values for variables were determined for all events where $P_{tot} \geq 0.15$ inch, and $P_s \geq 0.033$ inch. The *MLR* program was run with the data for all four watersheds lumped together (Table 4). The minimum values of depth and intensity were chosen from infiltrometer data and other sources that indicated that lesser depths and intensities could not, under natural conditions, produce runoff on these watersheds.

TABLE 3. Prediction Equations for Runoff Volume and Peak Rate of Runoff for the Lucky Hills Watersheds (Using Variables Significant to the 1% level)

Watershed	
LH-3	$Q = 0.48\ P_{tot} - 0.004\ D_{pd} - 0.076$
LH-4	$Q = 0.33\ P_{tot} - 0.24\ P_{ac} - 0.10$
LH-5	$Q = 0.41\ P_{20} - 0.073$
LH-6	$Q = 0.33\ P_{tot} - 0.003\ D_{pd} - 0.057$
LH-3	$Q_{pr} = 2.4\ P_{15} + 0.003\ D_{pt} - 0.65$
LH-4	$Q_{pr} = 1.7\ P_{tot} - 1.4\ P_{ac} - 0.50$
LH-5	$Q_{pr} = 3.7\ P_{10} - 0.50$
LH-6	$Q_{pr} = 2.8\ P_{10} - 0.45$

TABLE 4. Prediction Equations for Runoff Volume, Peak Rate of Runoff, and Duration of Runoff for the Lucky Hills Watersheds (Significant at the 1% level)

$Q = 0.37\ P_{15} + 0.0002\ D_{pt} - 0.065$,	$R^2 = 0.68$
$Q_{pr} = 1.8\ P_{15} - 0.23$,	$R^2 = 0.68$
$D_{rt} = 120.\ P_{10} - 3.4\ S_a + 16.$,	$R^2 = 0.39$

When all significant events were included, the 15-minute depth of rainfall became the dominant variable for determining runoff volume and peak rate of runoff. Both runoff and peak rate were also strongly correlated to the 10- and 20-minute depths of rainfall. The prediction equation for duration of runoff based on P_{10} was significant at the 1% level, but only about 40% of the variance was accounted for by P_{10} and the watershed slope combined (Table 4).

Run No. 3—Correlation of runoff variables for all watersheds with independent variables and watershed parameters for runoff-producing storms.

All variables were included in this run, but only for runoff-producing events, in an effort to find meaningful prediction equations for lag time and rise time and a better equation for flow duration (Table 5).

Significant prediction equations were derived for total runoff, peak runoff, runoff duration, and lag time, but not for rise time. Again, for the limited number of events, total precipitation was the most significant variable for determining runoff volume, and peak rate of runoff was most influenced by the 15-minute depth of rainfall. The prediction equation for flow duration ($D_{rt} = 0.05\ L_{max} + 0.16\ D_{pt} + 2.49$) was both significant and reasonable. Flow duration was most positively correlated to the length of the watershed and was also significantly correlated to the duration of rainfall. Lag time was most positively correlated to area and also significantly correlated to duration of precipitation, but these variables accounted for only 34% of the variance. Since an area-lag-time relationship is reasonable, additional data might improve the correlation.

TABLE 5. Input Variables Determining Runoff Variables for Lucky Hills Unit-Source Watersheds: Entering Order of Variables and Significance

Dependent Variable	Entering Variables				
Q	P_{tot}	P_{10}	S_a	D_{pd}	A
R^2	$\underline{0.71}$	$\underline{0.77}$	0.81	0.83	0.85
Q_{pr}	P_{15}	D_{pt}	A	P_{30}	P_{10}
R^2	$\underline{0.76}$	$\underline{0.80}$	0.82	0.83	0.85
D_{rt} (flow duration)	L_{max}	D_{pt}	D_{pd}	A	...
R^2	$\underline{0.50}$	$\underline{0.60}$	0.63	0.66	...
T_r (rise time)	P_{oa}	A	D_{pd}	...	...
R^2	0.06	0.10	0.14	...	...
T_1 (lag time)	A	D_{pt}	S_a		
R^2	$\underline{0.27}$	$\underline{0.34}$	0.37		

——— Significant at 1% level.

Run No. 4—Correlation of logarithmic transformation of runoff variables for all watersheds with logarithmic transformation of independent variables and watershed parameters for all runoff-producing storms.

In an effort to improve the prediction equations, all data were introduced into the *MLR* program and transformed to log form. Somewhat surprisingly, log transformations did not improve the prediction equations for any of the runoff variables. In fact, the coefficients of determination were lower for the logarithmic equations for both runoff volume and peak rate of runoff. For flow duration the log equation was about as significant as the simple linear regression equation. Therefore, at least with the available data, simple linear regression equations provide the best models for precipitation-runoff relationships for these brush-covered unit-source watersheds ranging in size from ½ to 11 acres.

CONCLUSIONS

The range, the mean or expected value, and the standard deviation of the data for the three years of record were also calculated. Comparison of these data with those for other subunits of Walnut Gulch indicates that none of the more intense storms has been experienced in Lucky Hills. On other parts of the Walnut Gulch watershed, we have had rains in excess of 2 inches in less than 30 minutes on many occasions.

Possibly the linear regression models as hypothesized by Schreiber and in this paper will not accurately predict the parameters for these exceptional events. Therefore, the authors hope to extend the analysis to other larger subwatersheds on the Walnut Gulch Experimental Watershed where the previously mentioned storms have occurred.

However, the present range of data probably represents more than 95% of the range in precipitation from individual summer thunderstorms. In other words, we have a fairly good representation of the high-frequency events, but not of the low-frequency events. It may be that the low-frequency events need to be treated separately and that two sets of equations should be developed for this region, one for general water yield estimates and the other for flood estimates.

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