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Regression Models for Predicting On-Site Runoff from Short-Duration Convective Storms[1]

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Abstract. On-site runoff resulting from summer convective thunderstorms was studied in the Walnut Gulch Experimental Watershed, using 6- × 12-foot plots at 2 locations, based on 5 location-years of data from 34 storms. Average runoff increased as precipitation quantity increased, decreased as crown spread of vegetation increased, and decreased as antecedent soil moisture increased. In a stepwise multiple linear regression equation, these independent variables accounted for, respectively, 72, 3, and 0.5% of the prediction variance. Considering regression equations for any one location-year, storm amount or intensity always was significant, crown spread usually was significant, and antecedent soil moisture rarely was significant. In simple correlations, antecedent soil moisture was never related significantly to runoff. The equations developed appear valid for a set of thunderstorms with at least one-sixth of maximum 5-minute intensities exceeding 3.7 inches per hour. (Key words: Hydrology; runoff; thunderstorms)

INTRODUCTION

Storm runoff in southern Arizona and New Mexico occurs almost exclusively from short duration, high-intensity, convective summer thunderstorms of small areal extent, as discussed by *Osborn and Reynolds* [1963]. These storms thus produce the water that ephemeral streams carry to storage for this region's irrigation purposes. Here the storms are usually associated with convective activity. However, they may permit a comparison with the hydrologic phenomena that might result also from the more intense portions of eastern frontal storms.

The convective thunderstorms themselves, and the runoff resulting from these storms, have been studied in the Walnut Gulch Experimental Watershed in southeastern Arizona for 12 years. It has been observed qualitatively that storms with similar characteristics of amount and intensity, falling on the same area within a few days of each other, produce about the same amount of runoff. The inference is that runoff is largely controlled by storm characteristics and not by antecedent soil moisture.

Partial confirmation of the importance of storm characteristics was found also in a study of peak runoff rates and volumes from seven small watersheds near Safford, Arizona, and Albuquerque, New Mexico. *Keppel* [1965] found that at these locations total precipitation and two intensity variables correlated positively with runoff. No significant correlation existed between 5-day antecedent rainfall and runoff, with these high intensity storms.

The *Soil Conservation Service* [1964] has computed runoff Q for a given watershed as a function of the difference between storm quantity P and maximum potential difference between P and Q, S, in inches at the time of a storm's beginning

$$Q = (P - 0.2S)^2/(P + 0.8S)$$

Its handbook states that S is dependent on soil-water storage and the infiltration rates of a watershed. The present work indicates that, at least for the study area, antecedent soil-water may be of little consequence in predicting runoff from convective storms. Possibly, runoff originating from more intensive parts of frontal-convective storms in other areas is likewise

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TABLE 1. Means and Standard Deviations (SD) of Variables, per Storm (34 Storms Studied)

	Precipitation (P)		Max. Int. (I)		Antecedent Soil Moisture (ASM)		Basal Area (BA)		Crown Spread (CS)		Runoff (Q)		Mean Runoff	
	Mean, inches	SD,*	Mean, in./hour	SD,*	Mean, log ohms resistance	SD,*	Mean, ft/66′	SD,*	Mean, ft/66′	SD,*	Mean, in.	SD,	Mean	P/Season
TU-8														
1963	0.676	0.384	2.51	1.31	3.29	0.488	1.07	0.565	8.89	4.29	0.287	0.279		0.42
1964	0.783	0.565	2.19	1.60	3.56	0.951	2.94	1.43	33.69	7.89	0.231	0.311		0.29
1965	0.610	0.267	2.42	0.625	3.92	1.212	3.95	1.57	35.43	8.65	0.081	0.091		0.13
TU-9														
1964	0.818	0.298	2.57	0.655	3.22	0.544	...	...	20.27	8.76	0.267	0.173		0.33
1965	0.770	0.593	2.14	2.00	3.79	0.603	...	...	10.94	8.40	0.210	0.264		0.27
													X =	0.288

* Standard Deviation.

unaffected by antecedent soil-water. Plots established to show effects of range treatment on rain-site runoff afforded an opportunity to study the effects of storm characteristics, antecedent soil moisture, and some plant parameters on runoff generation, almost free from the influence of runoff originating on higher ground and contributing to the plot's soil moisture.

PROCEDURE

Metal-bordered 6′ × 12′ plots were set up in two locations, 24 plots per location. At the start of the experiment, one location (TU-8) was desert grassland with an admixture of shrubs. The soil there is tentatively classified as Hathaway gravelly sandy loam. The other location (TU-9) was dominated by a shrub cover at the start of the experiment and the soil tentatively classified as Rillito gravelly sandy loam. The TU-8 plots were treated with fertilizer and supplemental water [*Schreiber and Kincaid*, 1966]. The TU-9 plots were subjected in a factorial experiment to brush clearing, land surface pitting, and reseeding to grass [*Kincaid and Williams*, 1966].

Total runoff per storm was caught and meas-

TABLE 2. Correlations (simple) between Variables

	P	*I*	*ASM*	*BA*	*CS*	*Q*
TU-8-1963						
P	1.00	0.8481†	−0.1079	0	0	0.9338†
I		1.00	−0.1204	0	0	0.6760†
ASM			1.00	−0.0905	0	−0.0671
BA				1.00	−0.2208	−0.0088
CS					1.00	0.00114
Q						1.00
TU-8-1964						
P	1.00	0.8711†	−0.0883	0	0	0.8882†
I		1.00	−0.1436*	0	0	0.8914†
ASM			1.00	−0.0881	−0.1437*	−0.0894
BA				1.00	0.3669†	−0.1078
CS					1.00	−0.1220*
Q						1.00
TU-8-1965						
P	1.00	0.8465†	−0.2898†	0	0	0.4948†
I		1.00	−0.5271†	0	0	0.5188†
ASM			1.00	−0.4118†	−0.2927†	−0.0445
BA				1.00	0.3386†	−0.3361†
CS					1.00	−0.2893†
Q						1.00
TU-9-1964						
P	1.00	0.843†	−0.206*		0.00860	0.582†
I		1.00	−0.139		−0.00805	0.700†
ASM			1.00		0.0318	−0.0977
CS					1.00	−0.369†
Q						1.00
TU-9-1965						
P	1.00	0.998†	0.348†		0.000	0.928†
I		1.00	0.387†		0.000	0.927†
ASM			1.00		0.074	0.358†
CS					1.00	−0.093
Q						1.00

* Significant at 5% level
† Significant at 1% level

P = Precipitation, total/storm
I = Intensity, maximum 5 minute
ASM = Antecedent soil moisture
BA = Basal area
CS = Crown spread
Q = Runoff

TABLE 3. Variables: Entering Order, Significance of Contribution to Regression, and Resultant Multiple Correlation Equation Coefficient

TU-8					
1963	*P*†	*I*†	*ASM*	*BA*	*CS*
R^2	0.8720	0.9198	0.9203	0.9204	0.9204
1964	*I*†	*P*†	*CS*†	*ASM*†	*BA*†
R^2	0.7945	0.8463	0.8612	0.8691	0.8742
1965	*I*†	*BA*†	*CS**	*P*	*ASM*
R^2	0.2691	0.3821	0.4169	0.4278	0.4297
TU-9					
1964	*I*†	*CS*†	*ASM*	*P*	
R^2	0.4902	0.6227	0.6228	0.6228	
1965	*P*†	*CS**	*ASM*	*I*	
R^2	0.8611	0.8698	0.8718	0.8725	

* Significance at 5% level.
† Significance at 1% level.

ured in buried 55-gallon drums. Rainfall was measured at each location by recording gages having a time resolution of 1 minute. Data for basal area and crown spread were derived from vegetational surveys made at least annually after the summer growing season. The vegetation measurements for a given plot obtained at the end of the season were assumed to exist at each storm. During the experimental period there was a general increase in vegetation, but it can be assumed that the within-plot seasonal changes are negligible as compared with the plot-to-plot differences.

Antecedent soil moisture (*ASM*) was monitored with gypsum electrical resistance blocks, set at various depths beginning at 3 inches. Block readings were made daily, or often enough to permit extrapolation to a probable resistance. Raw input data for antecedent soil moisture are the logarithms of the resistance of the 3-inch block the morning of the storm. The supposition is that the upper blocks reflect the crustal soil moisture also. If two storms occurred on consecutive days, and it was not possible to read blocks immediately after the first storm, the soil was assumed to have reached field capacity and the blocks a resistance of 1000 ohms.

Three indices of precipitation were examined for their importance: total quantity per storm in inches; maximum 5-minute intensity in inches per hour; and duration of storm in minutes.

All six independent variables: depth (*P*), intensity (*I*), time (*D*), basal area (*BA*), crown spread (*CS*), antecedent soil moisture (*ASM*), and the dependent variable, runoff per plot per storm, were fed into a digital computer using a stepwise multiple linear regression program.

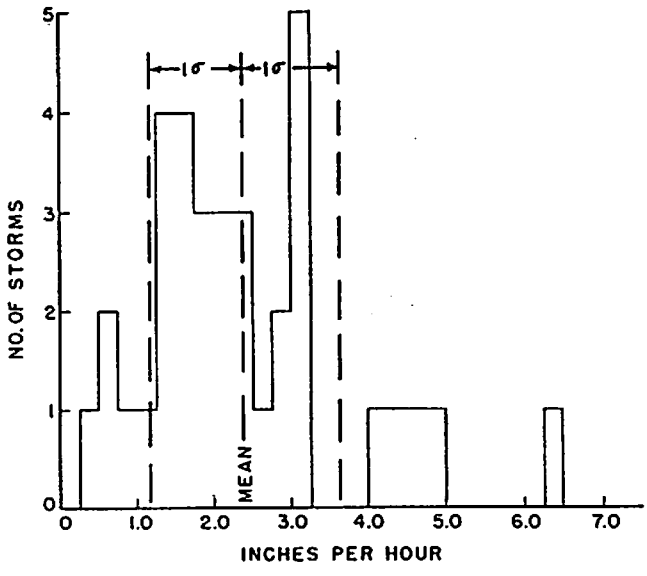

Fig. 1. Histogram of the maximum 5-minute intensities of the 34 runoff-producing storms observed in this study.

At any stage of the stepwise procedure only one variable is either entered or removed from the regression equation, and a variable to be removed takes priority over the one to be added. The contribution of a variable in reducing the variance is considered for all variables in the regression equation. If the contribution of a particular variable is insignificant (at a specified F-level), this variable is removed, otherwise the variance reduction for all variables not in the regression equation is considered. The variable which reduces, most significantly, the variance (and the calculated F-level exceeds a specified F-level to include variables) is then added to the regression equation. If there are no additional variables to be examined, or both of the above significance tests fail, the algorithm is terminated. [*Huszar*, 1966]

A multiple regression coefficient R^2 is determined and is the ratio of the regression sum of squares to the total sum of squares.

RESULTS

Individual location–year storm sets. Results of a total of 34 runoff-producing storms are reported in this study. Precipitation amount per storm averaged 0.70″ and ranged to more than 1.50″. The runoff-producing part appears in all cases to have been restricted to less than 40 minutes.

The means and standard deviations for all the independent variables and runoff are shown in Table 1. Although considerable variation was obtained in mean summer-season yields of water, the average yield of 28.8% per season represents three of the five sets of data. Nonhomogeneity of error variance for runoff between TU-8 and TU-9 for 1964 is indicated by bare significance at the 5% level of the ratio of the respective error mean squares. A t test requiring homogeneity of these variances may therefore be incorrect, but if a pooled error variance can be considered homogeneous, then no significant differences in runoff exist between locations for 1964.

The mean precipitation per storm differed little from year to year, but the standard deviations of P and I indicate the otherwise large variation in annual storm characteristics (Table 1).

Table 2 lists the simple correlations between all the variables. It shows that highly significant positive correlations always existed between P and I, even in years with no high-intensity storms, and between P or I and Q. With one exception, *ASM* never correlated simply with Q, and that exception was anomalous within this study in that Q increased as the antecedent soil moisture decreased. Plant parameters correlated highly significantly when cover amount became quite high or marked differences existed within the experimental area (no cover versus normal to good). Otherwise, the normal percentages of cover, whether grass or shrub, could not affect runoff until statistical adjustments had been made with the more dominant storm variables.

Table 3 shows the main findings of the computer analysis program by locations and years: the order of entry of the independent variables, whether their contribution to the regression equation was significant, and the resultant multiple correlation coefficient with the entrance of each variable.

Either P or maximum 5-minute intensity I was the most important single variable affecting Q. In three of the five station-years, precipitation amounts accounted for 80% or more of the

TABLE 4-1. Combined Regression Equations

TU-9 (1964–1965)	Mean	Standard Deviation
P	0.802	0.419
I	2.427	1.282
ASM	3.410	0.623
CS	17.16	9.68
Q	0.248	0.209

No. of observations = 216

Simple Correlations

	P	I	*ASM*	*CS*	Q
P		0.939†	−0.0496	0.02849	0.783†
I			0.08448	0.06965	0.820†
ASM				−0.1569†	0.04310
CS					−0.1595†
Q					

Order of Variable Entry and Significance

	I†	*CS*†	*ASM*	P
R^2	0.6723	0.7195	0.7234	0.7235

Prediction Equations	Standard Error of Q (inches)
$Q = -0.07665 + 0.1336\ (I)$	0.1199
$Q = -0.001993 + 0.1361\ (I) - 0.004700\ (CS)$	0.1112

† Significance at 1% level.

variance in Q. In the other two cases, I was the most important variable but, alone, accounted for less than 50% of the variance. The years with some storms of high intensity can better use amount per storm as a predictive variable for runoff from a given storm than when intensities and quantities are low. The first two years of TU-8 records show that using both P and I significantly improved the prediction equation. However, intercorrelations of P and I are often as high as either with Q, so that no consistent improvement in prediction was seen if both P and I were used.

Examination of each year-location storms' set of maximum 5-minute intensities (Figure 1) discloses that if 68% did not exceed 3.3″ per hour, and 95% did not exceed 3.9″ per hour, then precipitation quantity was not as good an indicator of runoff as intensity. For example, at TU-9 in 1964, no high intensity storms occurred, and intensity jumped from last to first in importance. If these limits were raised to 3.7″ per hour and 5.0″ per hour, respectively, then yearly average intensities could be deemed to be high, and storm quantity would be adjudged the determining variable for runoff.

Usually one other variable, the other storm parameter or a plant parameter, made a highly significant contribution to the regression equation, although the improvement in runoff prediction was slight in terms of percentage. In only one case did ASM make a significant contribution in any one year.

The small dependence of Q on ASM makes it appear that determining Q by the unsatisfied moisture storage capacity to some limiting or restricting horizon is a very unworkable tenet for semiarid rangelands. Even for storms of long duration, if I is low enough, moisture penetration can be as deep as 6 feet with no runoff occurring.

Combined location–year sets. Table 4 lists

TABLE 4-2. Combined Regression Equations

TU-8 (1963-1965)

	Mean	Standard Deviation
P	0.659	0.412
I	2.367	1.324
ASM	3.459	0.8443
BA	2.390	1.598
CS	24.97	13.92
Q	0.213	0.2608

No. of observations = 600

Simple Correlations

	P	I	ASM	BA	CS	Q
P	1.00	0.892†	−0.0307	−0.0261	−0.0279	0.876†
I		1.00	−0.0869	−0.0437	−0.0705	0.783†
ASM			1.00	0.0105	0.0643	−0.129*
BA				1.00	0.657†	−0.214†
CS					1.00	−0.219†
Q						1.00

Order of Variable Entry and Significance

	P†	CS†	ASM†	BA†	I
R^2	0.7668	0.8047	0.8127	0.8205	0.8211

Prediction Equations	Standard Error of Q, inches
$Q = -0.1523 + 0.5539\,(P)$	0.1260
$Q = -0.05893 + 0.5504\,(P) - 0.003647\,(CS)$	0.1154
$Q = 0.03541 + 0.5488\,(P) - 0.02773\,(ASM) - 0.003540\,(CS)$	0.1131
$Q = 0.04940 + 0.5481\,(P) - 0.02889\,(ASM) - 0.01910\,(BA) - 0.002096\,(CS)$	0.1109

* Significance at 5% level.
† Significance at 1% level.

TABLE 4-3. Combined Regression Equations

All Years and Locations

	Mean	Standard Deviation
P	0.697	0.418
I	2.38	1.31
ASM	3.446	0.7916
CS	22.90	13.38
Q	0.2218	0.2484

No. of Observations = 816

Simple Correlations

	P	*I*	*ASM*	*CS*	*Q*
P	1.000	0.8960†	−0.0175	−0.0545	0.8484†
I		1.000	−0.0521	−0.0465	0.7879†
ASM			1.000	−0.0358	−0.0999*
CS				1.000	−0.2173†
Q					1.000

Order of Variable Entry and Sign of R^2

	P†	*CS*†	*ASM*†	*I*†
R^2	0.7198	0.7492	0.7555	0.7587

Prediction Equations	Standard Error of *Q*, inches
$Q = -0.1290 + 0.5036\,(P)$	0.1316
$Q = -0.05216 + 0.4981\,(P) - 0.003187\,(CS)$	0.1246
$Q = -0.03285 + 0.4973\,(P) - 0.02486\,(ASM) - 0.003135\,(CS)$	0.1231
$Q = 0.01763 + 0.4291\,(P) + 0.02429\,(I) - 0.02339\,(ASM) - 0.003144\,(CS)$	0.1224

means, correlations, and variable entry order for combined years at the two locations and all the sets of data combined. The main points disclosed in this table are that: (1) *ASM* is not as important as the plant parameters; (2) *I* or *P* may be the dominant variable (considering the two locations separately); and (3) whereas all the parameters make significant contributions, inclusion of the second most important parameter, crown spread of vegetation, improved runoff prediction (R^2) only 3% over the 72% that was obtained from *P* alone.

The prediction equation including as variables only *P* or *I* as independent variables has a negative constant. The general equation ($Q = -0.1290 + 0.5036P$) constant of −0.1290 indicates that 0.129 of an inch of precipitation must fall before runoff begins. The corresponding equation relating *Q* to *I* has a constant of −0.1334.

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