VOLUME 2

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MAY 5-6, 1972, PRESCOTT, ARIZONA
SIGNIFICANCE OF ANTECEDENT SOIL MOISTURE TO A
SEMIARID WATERSHED RAINFALL–RUNOFF RELATION 1/

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INTRODUCTION

A series of reports from the Southwest have claimed or been interpreted
to claim that soil moisture prior to a rainfall–runoff event has no influence,
or possibly an inverse effect, on the resulting flow volumes and peak rates
[Keppel (1965), Schreiber and Kincaid (1967), Osborn and Lane (1969), Hickok
and Osborn (1969), Fogel and Duckstein (1970), Kisiel, Duckstein, and Fogel
(1971), and Osborn, Lane, and Kagan (1971)].

These reports cast doubt on the significance of antecedent soil moisture
in the semiarid convective rainfall–runoff relationship, but the evidence
presented is not conclusive. Further, the unimportance of soil moisture
is not consistent with the theory of the soil–watershed system (for an
example, consult Smith and Woolhiser, 1971) or with observation of the
records from the Safford and Albuquerque experimental watersheds operated
by the Agricultural Research Service, (USDA, ARS). Runoff occurs from
many storms that would not be expected to produce runoff and the explanation

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appears to lie in the occurrence of antecedent rains. One way to test
the significance of antecedent rainfall events is to divide the runoff
events into two subsets, one with no rain within the preceding 120 hours
(5 days) and another with some amount of rain within the preceding 24
hours and then test the null hypothesis ($H_0$):

Selected parameters of the flow hydrographs for two subsets
[(1) no rain within 120 hours and (2) rain (greater than
selected depths) within 24 hours] are of the same population.

If $H_0$ is rejected when the rainfall associated with both sets is similar,
then the contention that antecedent rainfall contributes to differences
in runoff would be supported.

**PROCEDURE**

The hypothesis was tested with rainfall and runoff data from a
40-acre ARS watershed located 22 miles west of Albuquerque, New Mexico.
This watershed is identified by ARS location code 47 and site number
002; thus, it will be identified by the number 47.002. The watershed
is described in "Monthly Precipitation and Runoff for Small Agriculture
Watersheds in the United States," 1957. All single-response runoff events
were selected from the runoff tabulation of Watershed 47.002 for the
analysis. The other category of events is multiple-response, which means
that several distinct runoff events resulted from a long, complex rainfall.
Each multiple-response could be associated with some part of the rainfall,
but this complication was avoided in a first test of the proposition.

The date, beginning time, peak rate of flow (cfs, in/hr), volume (in),
duration of flow (minutes), first moment of the stage record, and time to
peak (minutes) of each flow were tallied. With the date and beginning time of each selected runoff event, the rainfall data were searched and selected rainfall parameters were tallied for all rainfall events within 120 hours preceding each runoff event. The selected rainfall parameters were: average duration (min), Thiessen-weighted total depths (in), average maximum 5-min. intensity (in/hr), average maximum 15-min. intensity from an individual gage, average histogram centroid, and time (hours) before a runoff event began.

The runoff events were divided into two sets—one with rainfall in the preceding 24-hour period and one without any rainfall in the preceding 120-hour period. Rainfall parameters corresponding to events in these two sets were compared with a Wilcoxon's Rank Sum Test to determine if the two subsets of runoff came from the same rainfall population. If the rainfall of the two runoff events were of the same population, then the null hypothesis with respect to each of the runoff parameters was tested using Wilcoxon's Rank Sum Test.

**WILCOXON'S RANK SUM TEST**

The distributions of the rainfall-runoff parameters were not determined but it is known that most of them are not normal distributions. The Wilcoxon's Rank Sum Test is a distribution-free test for identical populations that is sensitive to unequal location. This statistical test was used to test the stated hypothesis. Definition of the test, statistics, and discussion of the test procedure may be found in Bradley (1968). The only condition that must be met for use of this test is that each population contain an
infinite number of units, or that the sampling is with individual replacement (Bradley, p. 107). An infinite population will be assumed for the conditions of the reported tests inasmuch as rainfall and runoff events were selected from 30 years of historical records. Some sets of data had many ties and they were treated as recommended (Method A) by Bradley (1968, p. 49-50).

RESULTS

The results of the Wilcoxon statistical tests are summarized in Tables 1 and 2. The parameters are identified by the following symbols:

- $D$: Total rainfall depth (inches)
- $R_5$: Average maximum 5-minute rainfall intensity (in/hr)
- $R_{15}$: Average maximum 15-minute rainfall intensity (in/hr)
- $\text{Dur}$: Duration of rainfall or flow event (min.)
- $R_{M1}$: First moment of rainfall histogram (min.)
- $Q_t$: Total runoff volume (in.)
- $Q_p$: Maximum flow rate (in/hr)
- $T_p$: Time from beginning of flow event to maximum flow rate (min.) (time to peak)
- $Q_{M1}$: First moment of flow stage record (min.)

A two-tailed probability of $\alpha = .05$ of making a Type I error was selected as the threshold at which to accept or reject the null hypothesis.
DISCUSSION

Comparison of Rainfall Sets.

The first statistical test (A-1 of Table 1) made on the rainfall parameters rejected the hypothesis that the two rainfall subsets (wet and dry) were the same population with respect to rainfall depth. When the frequency distributions of rainfall depths for the two subsets were examined (see Figure 1), the wet subset had ten events with rainfall depths of 0.10 inch or less that were not in the dry set. Upon eliminating all events with depths of 0.10 inch or less, the statistical test accepted the hypothesis that the two subsets were from the same population (Test A-2, Table 1). The frequency distributions of the two subsets of Test A-2 are also shown in Figure 1.

The hypothesis that the two subsets were from the same population was next tested with respect to the 5-minute rainfall intensity (R5), and it was rejected (Test A-3, Table 1). The frequency distributions for these two subsets (see Figure 2) showed that the dry subset had only one event with R5 less than .70 inch/hour and that was a value of .30 inch/hour. The occurrence of runoff for that event (September 22, 1952) is questionable. So all events with R5 less than 0.70 inch per hour were eliminated and the statistical test again made with respect to the parameter, R5. The test (Test A-4) accepted the hypothesis that the two subsets (wet and dry) were of the same population.

Comparison of Tests A-5 and A-6 shows that eliminating depths of 0.10 inch or less did not necessarily make the two sets the same with
Table 1. Test results for 24-hour antecedent rainfall of any amount greater than 0 ($D_{24} > 0$) of the Null Hypothesis: $X$ parameter of the event with selected rainfall depth ($D_0$) and 5-minute intensity ($R_5$) causing runoff with (1) no rain within 120 hours and (2) rain of any amount greater than 0 ($D_{24} > 0$) within 24 hours are of the same population.

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<th>$D_0$</th>
<th>$R_5$</th>
<th>Parameter</th>
<th>Subset</th>
<th>$\alpha$</th>
<th>Reject $@ \alpha = 5%$</th>
<th>Also reject $@ \alpha = 5%$</th>
<th>Accept $@ \alpha = 5%$</th>
<th>Also accept $@ \alpha = 5%$</th>
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<td>$X$ 11.0</td>
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*Sets reduced by 17 events with no measurement of $R_5$. 390
Figure 1. Distributions of Rainfall Depths for Tests A-1 and A-2.
Figure 2. Distributions of 5-minute intensities for Tests A-3 and A-4.
respect to 5-minute intensities, and vice versa, eliminating all events with 5-minute intensities of less than 0.70 inch per hour did not make the two sets the same with respect to total rainfall depth. As a consequence, a double elimination based on both depth and 5-minute intensities must be made to obtain a set of rainfall events in which the subsets may be from the same population with respect to all rainfall parameters.

The data for Test A-5 had six events with rainfall depths between 0.09 inch and 0.13 inch—all in the wet subset. No events were in this range in the dry subset. Three dry events with depths of 0.12 inch had no measurement of the intensities, and these events were eliminated from the test data when the elimination of $R5 < 0.70$ in/hr was made. Because of the missing record, events with rainfall depths less than 0.14 inch and 5-minute intensities less than 0.70 in/hr were eliminated from the test data and the residual events were tested as being of the same population.

The residual sets of rainfall events were accepted as of the same population with respect to four of the five parameters. The null hypothesis was rejected with respect to rainfall duration. However in total, the two subsets of rainfall events can be considered to be of the same population and the runoff events tested for the influence of antecedent rainfall events. Before these tests are discussed, the obvious conclusions of the tests of the rainfall will be summarized.

The tests on the rainfall data alone demonstrate that rainfalls of less than 0.10-inch depth and 5-minute intensities of less than 0.70 inch
per hour will cause surface runoff if there is rainfall in the preceding 24 hours. These limits on depth and rainfall intensity apply to the particular 40-acre watershed tested. Two rainfalls of 0.10-inch depth and one of 0.09 inch with 5-minute intensities greater than 0.70 inch/hour caused runoff when there had been antecedent rainfall. Also one event (July 23, 1954) with 0.08-inch depth and 0.52-inch/hour 5-minute intensity caused considerable runoff when it followed a rainfall-runoff event by 3 hours.

Comparison of Runoff Sets for any Amount of Antecedent Rainfall.

When the A set (Table 1) parameters of the runoff events were tested for being of the same population, total runoff volume and peak discharge rate were accepted as being of the same population. However, the ratios of total runoff to total rainfall volume and peak discharge rate to the 5- and 15-minute average rainfall rates (Tests A-14, A-15, and A-16) were rejected as being of the same population. Also the tests rejected the null hypothesis for the two subsets (wet and dry) with respect to total flow duration and first moment of the stage hydrograph (Tests A-18 and A-19). But the null hypothesis was accepted with respect to time to peak. These tests were made for any depth of rainfall within the preceding 24 hours determining a "wet" event, and they show definitely that runoff volume from a given rainfall rate will be greater with antecedent rainfall. This trend is shown more definitely when rainfall depths above a given threshold are used to define a "wet" antecedent event. A threshold of 0.09 inch was used in the tests summarized in Table 2.
Table 2. Test results for 24-hour antecedent rainfall amount greater than 0.09 inches \((D_{24} > 0.09)\) of the Null Hypothesis: \(X\) parameter of the event with selected rainfall depth \((D_0)\) and 5-minute intensity \((R_5)\) causing runoff with (1) no rain within 120 hours and (2) rain of an amount greater than 0.09 inches \((D_{24} > 0.09)\) within 24 hours are of the same population.

<table>
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<th>(R_5)</th>
<th>(X)</th>
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<th>Number in (2)</th>
<th>(\alpha)</th>
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Comparison of Runoff Sets for $D_{24} > 0.09$ inch.

The same procedure was followed, testing the rainfall parameters of the two subsets (wet and dry). After the double elimination, the two subsets were accepted as being of the same population with respect to all five rainfall parameters.

The depths and time distribution of the antecedent rainfall for the wet subset are shown in Figure 3. On the average the accumulated rainfall was 0.29 inch (Figure 3a) occurring 14 hours (Figure 3c) before the runoff event. The distribution of times that an antecedent rainfall occurred prior to a rainfall-runoff event is rather uniform whereas the distribution of individual antecedent rainfall amounts (Figure 3b) is skewed with a mode in the 0- to 0.10-inch interval, markedly less than the mean depth of 0.17 inch.

When the antecedent rainfall was greater than 0.09 inch, the null hypothesis was rejected very conclusively with respect to runoff volume, ratio of runoff volume to rainfall depth, ratios of peak flow rate to average 5- and 15-minute intensities, flow duration, and first moment of the stage hydrograph. The test results were inconclusive with respect to peak flow rate, and they accepted the null hypothesis with respect to time to peak.

The comparison between distributions of the wet and dry subsets for the Tests B-13 and B-19 are shown in Figures 4 through 11. These tests were made and the conclusions drawn knowing that there were discharge rating inaccuracies, but since the statistical tests were making relative
Figure 3. Distribution of Depths and Time for Antecedent Rainfalls greater than 0.09 inch.
comparisons it was assumed that these rating errors would not affect the conclusions.

The distributions of runoff volumes (Figure 4) show the mean runoff volume of wet events is greater than that of dry events. Dry events overwhelmingly produce very little runoff. The first interval has been divided in half to further illustrate this tendency, but the greatest runoff volume resulted from a dry event (August 24, 1957).

The null hypothesis could neither be rejected nor accepted with respect to peak discharge rate. The distributions of Figure 5 show the occurrence of more small events under dry conditions (the 0-10 interval has been divided at 1 to illustrate this point), but again the four largest peak discharges of either set were from dry events.

When runoff volume relative to the associated rainfall volumes are compared, the null hypothesis is strongly rejected. The distributions of Figure 6 show the mean of the wet events to be considerably greater than that of the dry events. Thus, in general, more runoff results from a given rainfall depth when there has been antecedent rainfall. Again, the dry events have a significant cluster in the lowest interval (0.00-0.05), but two dry events stand out as producing a large ratio of runoff volume to rainfall volume. For one of the wet events (August 14, 1964), runoff was greater than rainfall. An examination of the original records reveals no apparent problems other than the obvious question of how could such a large flow have resulted from such a small event. It is known that the rating relations for the flow measuring weirs are inaccurate, but even
FIGURE 4. RUNOFF VOLUME DISTRIBUTIONS (TESTS B-12)

FIGURE 5. MAXIMUM FLOW RATE DISTRIBUTIONS (TESTS B-15)

FIGURE 6. VOLUME RATIO DISTRIBUTIONS (TESTS B-14)

FIGURE 7. RATE RATIO DISTRIBUTIONS (TESTS B-15)
these rating errors may not explain this anomalous event.

The ratios of peak flow to average 5- and 15-minute intensities were tested and their distributions are shown in Figures 7 and 8. Again the mean of the wet sets is significantly greater than that of the dry sets. Thus, in general, runoff rates relative to rainfall rates of the associated rainstorm will be higher when there has been antecedent rainfall. Again, the ratio distribution for dry events has a large cluster in the lowest interval (0-0.05), but three events have ratios as great as or greater than those determined for wet events. One ratio of peak discharge rate to average 15-minute rainfall intensity (Qm/R15) was greater than one. This is a plausible occurrence when a momentary runoff rate is compared with a 15-minute average rainfall rate.

Each of the dry set distributions for volume, maximum flow rate, ratio of runoff volume to rainfall volume, ratio of maximum flow rate to average 5- and 15-minute rainfall intensities had values as great as or greater than wet event distributions. These high values of the dry set are rather consistently associated with one of the five largest "dry" rainfall events. The rankings of the six largest events with respect to total average depth and average 5- and 15-minute intensities are shown in Table 3.

Two wet rainfall events appear in Table 3, but they are not associated with large values of wet runoff parameters (shown in Figures 4-11). The wet event of September 20, 1941, had high average 5- and 15-minute rainfall intensities but the total storm depth was relatively low at 0.73 inch.
FIGURE 8. RATE RATIO DISTRIBUTIONS (TESTS B-16)

FIGURE 9. TIME TO PEAK DISTRIBUTIONS (TESTS B-17)

FIGURE 10. DURATION DISTRIBUTIONS (TESTS B-18)

FIGURE 11. 1st MOMENT DISTRIBUTIONS (TESTS B-19)
Table 3. Ranking of 47,002 rainfall events with respect to average of two gage measurement of depths and intensities.

<table>
<thead>
<tr>
<th>Event Date</th>
<th>Dry Set</th>
<th>Wet Set</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>R5 in/hr</td>
</tr>
<tr>
<td>20 09 41</td>
<td>X</td>
<td></td>
<td>5.92</td>
</tr>
<tr>
<td>30 06 42</td>
<td>X</td>
<td></td>
<td>6.03</td>
</tr>
<tr>
<td>28 06 43</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>04 09 47</td>
<td>X</td>
<td></td>
<td>4.18</td>
</tr>
<tr>
<td>24 08 57</td>
<td>X</td>
<td></td>
<td>4.26</td>
</tr>
<tr>
<td>10 06 66</td>
<td>X</td>
<td></td>
<td>6.01</td>
</tr>
<tr>
<td>22 07 69</td>
<td>X</td>
<td></td>
<td>6.11</td>
</tr>
</tbody>
</table>
Also, the antecedent rainfall for this event was below average, with the 0.13 inch accumulated amount occurring at the limit of 24 hours (see Figure 3). The one wet rain that had the greatest depth (June 28, 1943) lasted 265 minutes, with maximum 5- and 15-minute intensities of 3.70 and 1.70 inches per hour.

Not the merest association could be made between large wet runoff events and large wet rainfall events as could be done for the dry set. The general situation of no association between high rainfall parameters and resulting runoff parameters for the wet set is indicative of an antecedent moisture influence. For the "dry" events there is one definite initial moisture state, but for the wet events the initial moisture ranged from nearly dry to very wet. Thus, the resulting runoff in the wet set is confounded by moisture state of the soil and the resulting largest volumes, peak flows, and ratios of volumes and rates were not associated with the largest rainfall events but rather a complex interaction between the input and the moisture state of the watershed system.

Comments on Definition of Wet Set.

The definition of a wet set as one in which rainfall equal to a greater than some selected depth falling within the preceding 24 hours is admittedly crude. Well-verified soil moisture accounting models and necessary physical data for semiarid rangelands are lacking; thus, as an expediency the antecedent rainfall definition for wet was used. It would have been preferable if these tests had been made on two sets in which the initial moisture state could have been determined more
directly, or with a "good" model and the wet set defined using soil moisture at the beginning of the rainfall-runoff event equal to or greater than some selected level. The set of events would be altered by eliminating some in the wet set as being not wet enough and including some that had sufficient rainfall prior to 24 hours to contribute to the selected moisture state at the beginning of the event.

CONCLUSIONS

A distribution-free statistical comparison between two sets of convective rainfall-runoff events, one considered to have no soil moisture at the beginning of rainfall and one considered to be moist by virtue of antecedent rainfall, demonstrated conclusively that antecedent rainfall influences runoff from a semiarid watershed. This is in contrast to previously published conclusions, which may be insufficiently supported or poorly drawn from available evidence. For the tested watershed, runoff volumes, ratios of runoff volume to rainfall depth, and ratios of peak flow rate to 5- and 15-minute rainfall rate were greater when the initial state was "moist."
REFERENCES


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