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VOL. 15, NO. 6 WATER RESOURCES RESEARCH DECEMBER 1979

Dense Networks to Measure Convective Rainfall in the Southwestern United States

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Almost all rangeland runoff in the southwestern United States results from intense short-duration rainfall of limited-area extent. In 1953, two southwest rangeland watersheds, the 150-km² Walnut Gulch and 174-km² Alamogordo Creek watersheds, were selected by U.S. Department of Agriculture Agricultural Research Service scientists as outdoor laboratories to measure water yield from rangeland watersheds. The networks were planned initially with gages on a 1-mi grid, but difficulties in access resulted in more uneven networks. Because of budgetary restraints the basic networks were not completed until 1961. Gages were added after 1961, both for better estimates of rainfall on very small intensive study areas and to fill 'gaps' in the original network. The values of these dense rain gage networks became more apparent as the full complexity of southwestern rainfall became more apparent. Interstation correlations for storm rainfall decrease very rapidly with distance between stations. Inadequate networks can lead to significant errors in either underestimating or overestimating rainfall input as well as underestimating rainfall variability in verification of hydrologic models developed, for example, to estimate peak discharge, sediment production, or channel recharge. Finally, there are regional differences in intensities, areal extent, and duration of convective rainfall in the Southwest which require adequate sampling at several locations within the region.

INTRODUCTION

Air mass and frontal convective thunderstorms are an important source of water throughout the southwestern United States. These thunderstorms produce the major flood peaks and almost all runoff from small (260 km² or less) southwest rangeland watersheds. For example, about 70% of the annual rainfall and essentially all runoff from rangelands in southeastern Arizona result from air mass thunderstorms [*Osborn and Hickok*, 1968]. In contrast, more massive frontal convective thunderstorms often occur in eastern New Mexico [*Osborn and Laursen*, 1973]. Frequencies of occurrence and estimates of the magnitude and extent of the thunderstorm rains are essential in predicting flood peaks, volumes, and sediment yields from all watersheds in the Southwest.

Air mass thunderstorms produce intense afternoon and evening rains of short duration and limited areal extent. Such storms are very important, for example, to the water supply of southern Arizona, but their nature makes measurement difficult. Unfortunately, as *Neyman and Scott* [1972] reported, 'Arizona is not very densely populated either by people or by raingages.' The same can be said for New Mexico. Therefore dense networks of recording rain gages in the Southwest may provide important additional rainfall information to that from widely scattered, long-term National Weather Service rain gage locations.

In this paper, two dense rain gage networks, one in Arizona and one in New Mexico, are evaluated. The discussion includes basic design concepts, early analyses and changes, economic and logistic limitations, and future value of such networks.

DESCRIPTION OF NETWORKS

In 1953 two southwest rangeland watersheds were selected by U.S. Department of Agriculture, Agricultural Research Service scientists as outdoor laboratories to measure water yield from rangeland watersheds. On the basis of information available at tne time, rain gage networks were designed with gages at 1-mi intervals on both experimental watersheds (the 150-km² Walnut Gulch and 174-km² Alamogordo Creek watersheds in southern Arizona and eastern New Mexico, respectively). The scientists felt that such 'dense' networks would be more than sufficient to measure any and all important aspects of runoff-producing thunderstorm rainfall.

Because access to some locations was difficult, actual gage locations varied from an idealized grid. The basic networks were not completed until 1961 because of limited funds. The Walnut Gulch network included three makes of 24-hour per chart revolution weighing-type recording rain gages, including triple-traverse gages manufactured in the 1930's. Only 6-in. single- or dual-traverse 24-hour recording rain gages were used on Alamogordo Creek. Initially, standard gages were located at many sites on Walnut Gulch until they could be replaced with recording gages. There were numerous clock failures in the early years of record, so a jeweler was hired to repair and maintain the clocks, and another aid was assigned to increase the frequency of servicing the gages.

From 1954 through 1964, many major runoff-producing thunderstorms were recorded on both watersheds. It became apparent when attempting to relate rainfall with runoff that the initial design density and the relaxed criteria for actual gage location, along with the unexpectedly small areal extent of air mass thunderstorms [*Osborn and Reynolds*, 1963], had left 'gaps' in the Walnut Gulch network and, particularly, within some of the instrumented subwatersheds. Therefore gages were added along the watershed boundary as well as on several subwatersheds, where intensive physical modeling studies were under way. By 1967 these additional gages brought the approximate density to one gage per 2 km². In contrast, preliminary analyses of some of the earlier frontal convective events on Alamogordo Creek [*Keppel*, 1963; *Osborn and Reynolds*, 1963] suggested that the network was dense enough to measure input satisfactorily from the more massive frontal convective events common in eastern New Mexico.

WALNUT GULCH THUNDERSTORMS

We selected three major thunderstorms on Walnut Gulch on August 17, 1957, July 22, 1964, and September 10, 1967, to

Paper number 9W0879

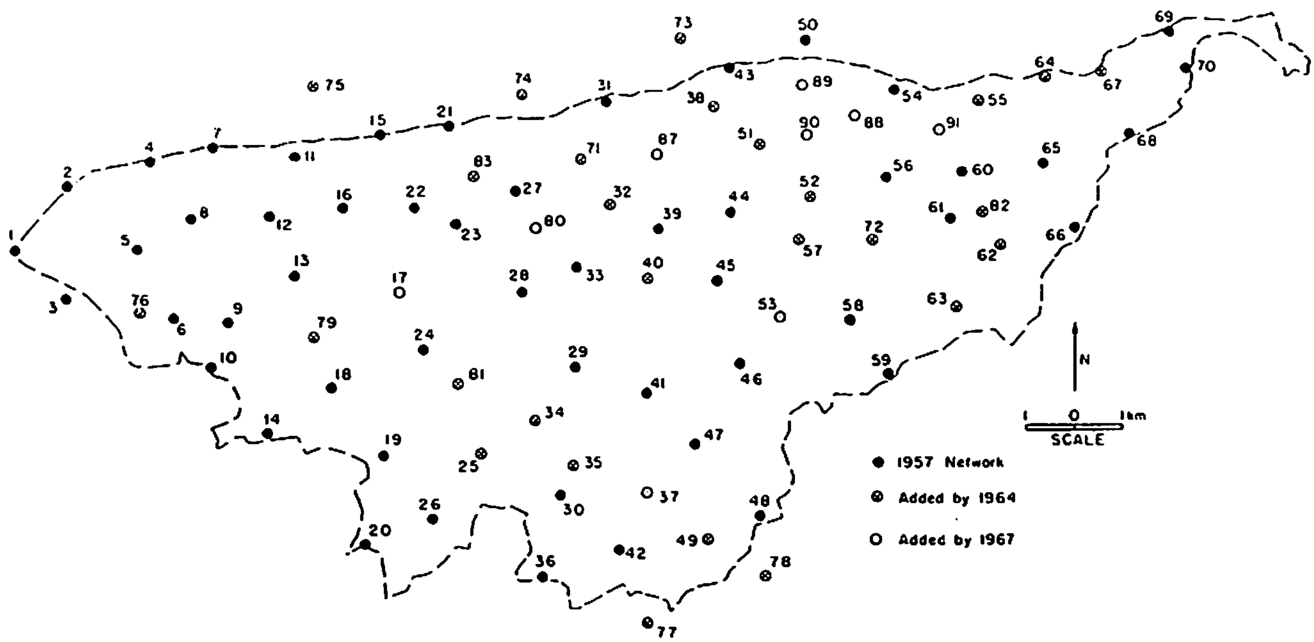


Fig. 1. Walnut Gulch recording rain gage networks in 1957, 1964, and 1967.

illustrate the evolution of both the rain gage network and our understanding of air mass thunderstorms and air mass thunderstorm runoff in southeastern Arizona. The networks for 1957, 1961, and 1967 on Walnut Gulch are shown in Figure 1. Fifty-two 24-hour recording rain gages were in operation in 1957; most were concentrated on the lower and central parts of the watershed. By 1964 we had added 27 gages; by 1967, another 9. In addition, there are several 6-hour recording rain gages on very small watersheds where we are carrying on research that requires greater precision and accuracy than can be obtained from the basic network of 24-hour rain gages.

Several investigators, including *Reich and Hiemstra* [1965] and *Osborn and Laursen* [1973], have reported that peak discharge from small rangeland watersheds like Walnut Gulch and its major subdrainages is best correlated to maximum 30-min rainfall and that runoff volume is best correlated to total runoff-producing rainfall. Total runoff-producing rainfall in such air mass thunderstorms usually lasts less than 60-min but often more than 30 min. Therefore for this study, isohyetal maps were constructed for the maximum 30- and 60-min rains of August 17, 1957, and September 10, 1967. Figure 2 shows the maximum 30- and 60-min rain for September 10, 1967. All runoff-producing rainfall during the July 22, 1964, storm occurred in less than 30 min, so only the maximum 30-min isohyetal map was used. Hyetographs for the gage with the maximum depth for each of the three events are shown in Figure 3.

The three events were all centered in about the same area on W-6, an instrumented 95-km² subwatershed on Walnut Gulch, so both rainfall and runoff can be compared. The maximum 30-min rainfall depth-area relationships for W-6 are shown in Figure 4. On the basis of these curves we would expect the largest peak discharge during the 1957 storm, with the peaks during the 1967 and 1964 storms being respectively smaller. Actually, the peak discharge was greater for the 1964 storm than for the 1967 storm, with the 1957 peak, as expected, being considerably larger than the other two.

Osborn and Laursen [1973] developed an empirical rainfall–peak discharge equation based on maximum 30-min rainfall for Walnut Gulch W-6. On the basis of this equation the actual peak discharges for the 1957 and 1964 storms were much higher than predicted (Table 1). The prediction equation was developed using mostly small runoff events, but still the differences were large enough to question the accuracy in measuring the areal distribution of rainfall, runoff, or both and the reliability of the prediction equation. In this paper we have concentrated on the reliability of the rain gage network. If all other factors, such as rain gage accuracy and antecedent channel moisture conditions, were equal among the three events and we are accurately measuring peak discharge and have a reliable prediction equation, then there must have been greater depths of rainfall on the watershed than we recorded. The large differences between predicted and actual discharges suggest this.

To investigate this possibility, 30-min isohyetal maps for the 1967 storm were developed assuming that rain gage 52 (storm maximum) was missing and then assuming that we had only the 1957 network of gages (Figures 5 and 6). In both cases, the storm patterns were different from those made using the full 1967 network. Furthermore, the predicted peak discharge for the 1967 storm with the maximum gage removed was considerably below that with the gage included (Figure 4). Also, the gaps in the earlier networks (1957 and 1964 events) were no larger than the gap introduced by removing rain gage 52. When the 1957 network was used, predicted peak discharge was actually higher. Depth-area curves in Figure 4, based on the 1957 network, indicated a more massive storm. In other words, a sparser network can lead to overpredicting as well as underpredicting.

Rainfall volumes for the 1957 and 1967 storms, determined using Thiessen weighting (Figure 7), planimetering isohyetal maps, and an arithmetic average, are summarized in Table 2. In all cases, Thiessen-weighted averages produced the largest estimate highest and arithmetic averages lowest. However, the differences based on the 1967 network with or without rain gage 52 probably were insignificant. On the other hand, arithmetic averages were significantly less for the 1957 network.

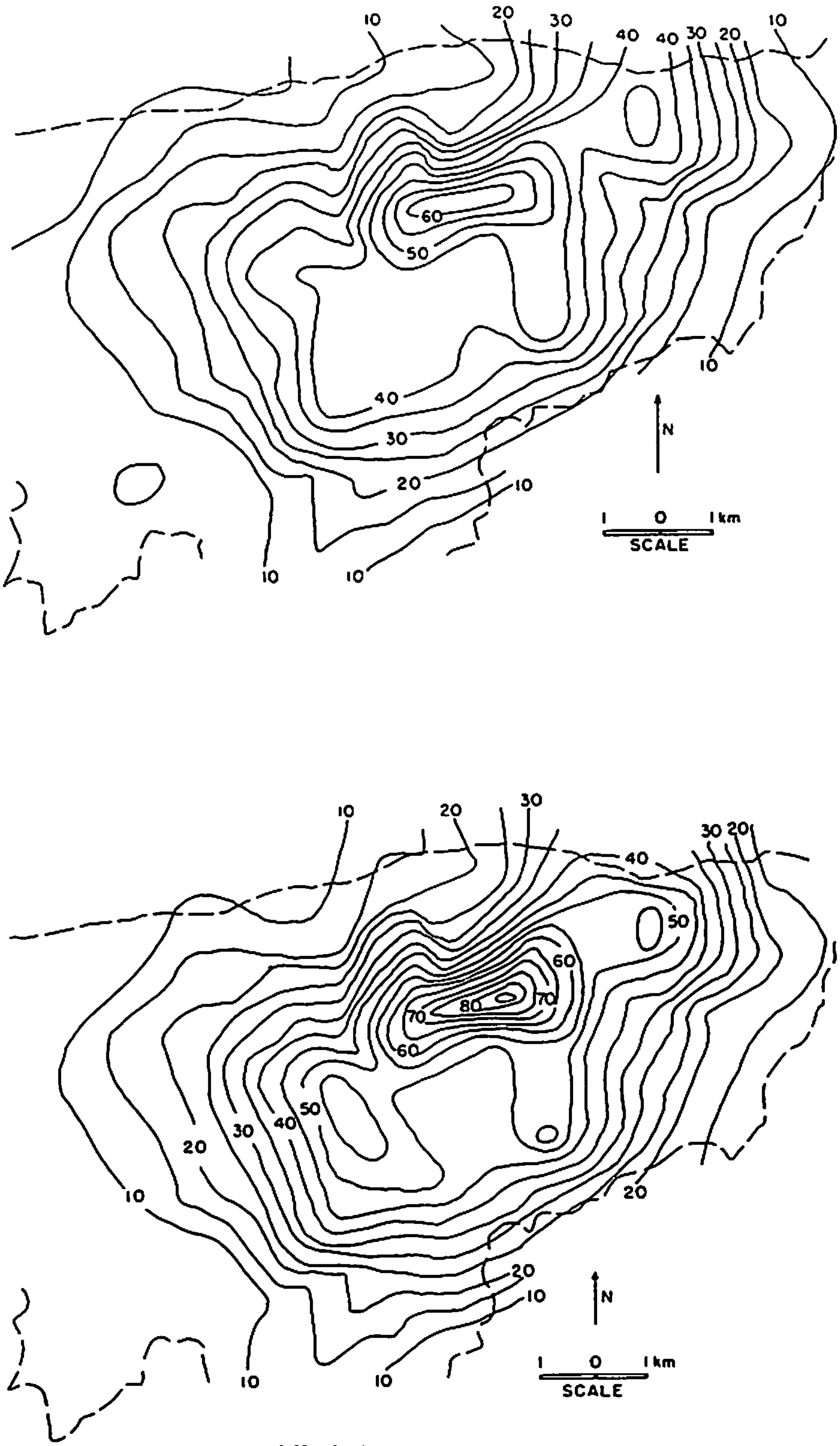


Fig. 2. Maximum 30-min (top) and 60-min (bottom) rainfall, Walnut Gulch, September 10, 1967.

ALAMOGORDO CREEK THUNDERSTORMS

We used three major thunderstorms on Alamogordo Creek on June 5, 1960 (Figure 7), June 16, 1966, and August 21, 1966 (Figure 8) to illustrate the more massive and occasionally longer lasting frontal convective thunderstorms that are common in eastern New Mexico. Hyetographs and depth-area curves for all three storms are shown in Figures 9 and 10. The 1960 storm, described by *Keppel* [1963] and *Osborn and Reynolds* [1963], produced the maximum point 60-min rainfall and the largest peak discharge in 20 years of record. The June 1966 storm was the second largest runoff-producing event [*Renard et al.*, 1970], and the August 1966 storm produced the maximum point 6-hour rainfall on Alamogordo Creek. The more massive nature of the three Alamogordo storms was obvious when we compared the isohyetal maps with those of three major events on Walnut Gulch. However, the majority of runoff-producing events on Alamogordo Creek are air mass

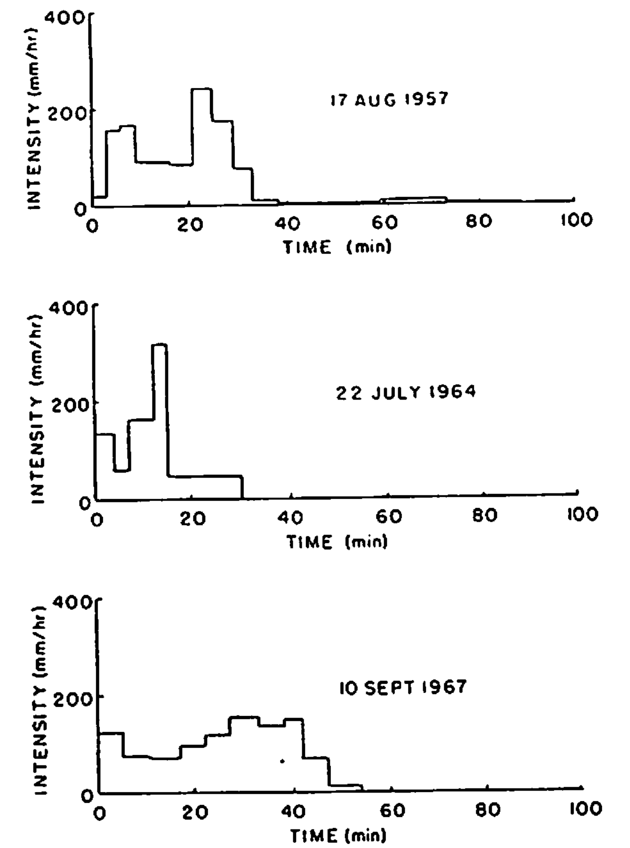


Fig. 3. Rainfall intensity with time for gages recording maximum rainfall for three selected storms on Walnut Gulch.

TABLE 1. Predicted and Actual Peak Discharges Q_a for Three Selected Events on Walnut Gulch W-6

	Q_a	
Date	Predicted m^3/s	Actual m^3/s
Aug. 17, 1957	214	294*
July 22, 1964	90	187
Sept. 10, 1967	159	131
Sept. 10, 1967†	131	131
Sept. 10, 1967‡	168	131

*Estimated.
†Without rain gage 52.
‡With 1957 network.

thunderstorms similar to those recorded on Walnut Gulch. Essentially, there are two populations of runoff-producing storms, and maximum depths and areal extents are significantly different within the two populations, thus suggesting that the two populations should be analyzed separately.

CORRELATION BETWEEN RAIN GAGES

On the Walnut Gulch watershed, precipitation intensities at four locations were measured with adjacent recording rain gages having 6-hour per revolution and 24-hour per revolution time scales. Maximum intensities for intervals up to 10 min determined from the 6-hour records were significantly greater than intensities determined from the 24-hour gage records for intervals up to 10 min [*Renard and Osborn*, 1966]. Although the study was undertaken to compare 6- and 24-hour records, it also indicated that there was no significant differ-

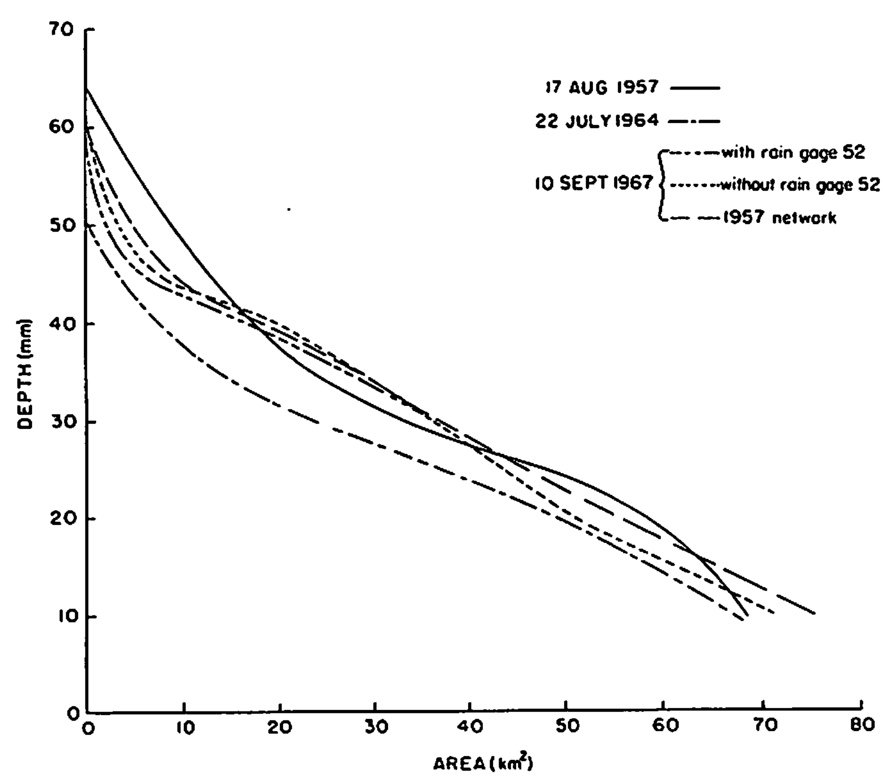
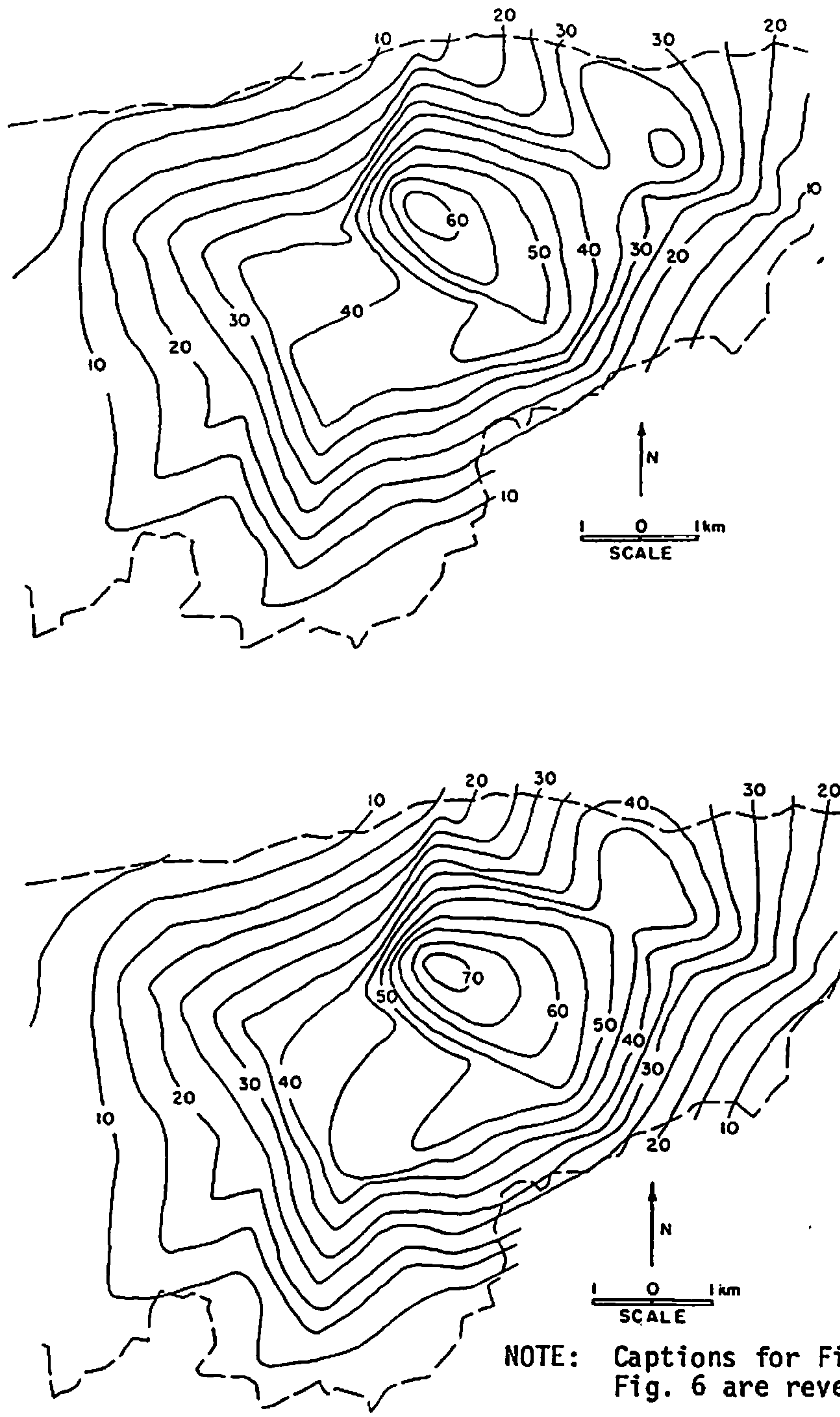


Fig. 4. Depth-area rainfall curves for Walnut Gulch W-6 subwatershed.



NOTE: Captions for Fig. 5 and Fig. 6 are reversed.

Fig. 5. Maximum 30-min (top) and 60-min (bottom) rainfall (in millimeters) for Walnut Gulch W-6 subwatershed on September 10, 1967, disregarding rain gage 52.

ence in rainfall catch for 15-min intervals and longer intervals for gages located within a few meters of one another.

Hershfield [1965] developed standards for rain gage networks based on $r \geq 0.9$. *Osborn and Lane* [1969] found that for very small rangeland watersheds (4 ha and less), peak discharge was most strongly correlated to maximum 15-min rainfall. *Osborn et al.* [1972] looked at the correlation between gages for maximum 15-min rainfall and total storm rainfall and determined that for $r \geq 0.9$, gages must be spaced at 300 and 500 m respectively. They noted that a spacing of 300 m would require a network of 1400 gages for the 150-km^2 Walnut Gulch watershed. The cost and change involved in establishing and trying to operate such a dense network are prohibitive.

As stated earlier, *Reich and Hiemstra* [1965] and *Osborn and Laursen* [1973] found that peak discharge for rangeland watersheds was best correlated to maximum 30-min rainfall for watersheds up to 200 km^2. On the basis of these earlier studies,

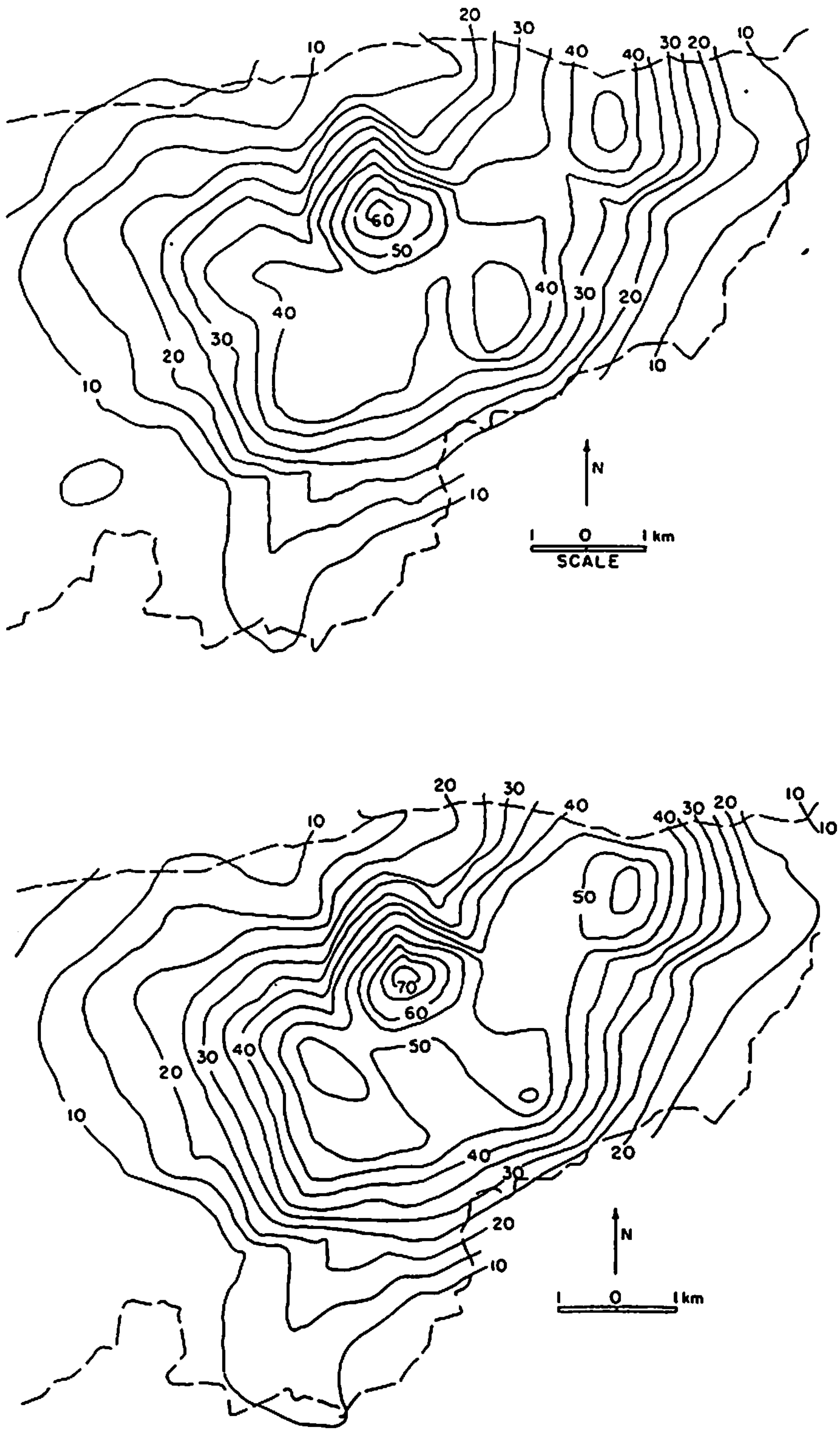


Fig. 6. Maximum 30-min (top) and 60-min (bottom) rainfall (in millimeters) for Walnut Gulch W-6 subwatershed on September 10, 1967, prepared using data from the 1957 network only.

correlations between gages were calculated for maximum 15-min, 30-min, and total storm rainfalls for Walnut Gulch and Alamogordo Creek to better identify the required (or desired) rain gage density for varying equivalents.

Correlation coefficients were calculated for total rainfall amounts during thunderstorms on Walnut Gulch and Alamogordo Creek. By using storm totals or maximum amounts for selected durations we assumed that we had eliminated time variability and that simple correlations between gages provided a useful indication of spatial variability. Twenty-six gages on Walnut Gulch and 13 gages on Alamogordo Creek with relatively long records were selected to provide as much variability in distances as possible without duplication and without having to compare all possible pairs of gages. Dis-

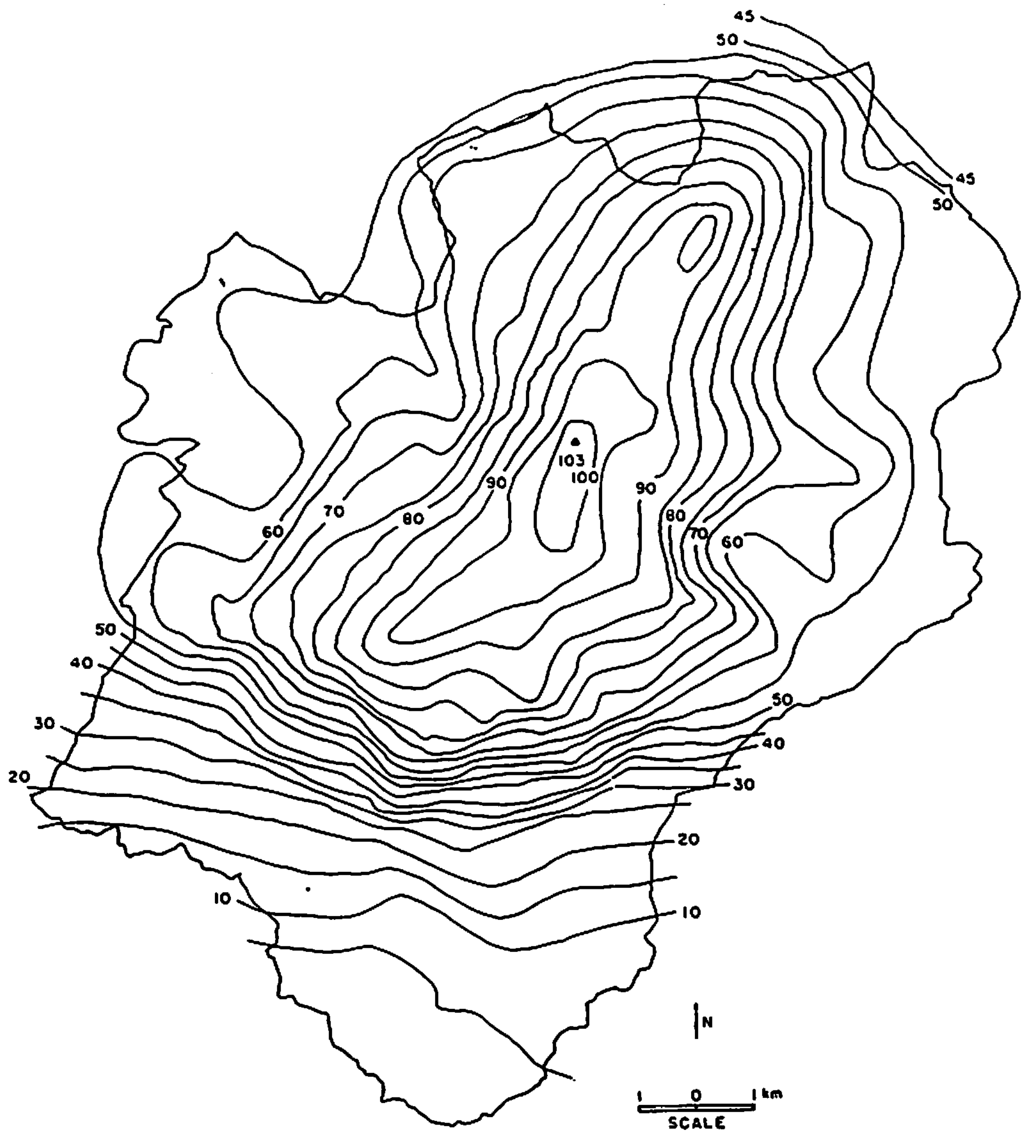


Fig. 7. Maximum 60-min rainfall (in millimeters), June 5, 1960, Alamogordo Creek.

tance between pairs of gages ranged from 0.8 to 23 km on Walnut Gulch and from 1.3 to 16 km on Alamogordo Creek. The relationships between correlation coefficient r and distance between gages for the two watersheds are shown in Figure 11. The correlation coefficient decreases more rapidly with distance on Walnut Gulch. For example, at 10 km, r is about 0.18 on Walnut Gulch as compared with 0.4 on Alamogordo Creek, and $r \simeq 0$ at 15 km on Walnut Gulch, while $r > 0.3$ at 15 km on Alamogordo Creek. For $r \geq 0.9$, distance between gages would be 0.8 and 1.32 km, respectively, which would require 230 and 100 gages on Walnut Gulch and Alamogordo Creek, respectively. As pointed out earlier, denser networks would be needed to delineate rainfall amounts for shorter durations.

The decrease in correlation between gages with distance, particularly on Walnut Gulch, suggests that for regions domi-

TABLE 2. Comparison of Three Methods for Evaluating Maximum 60-min Rainfall on Walnut Gulch

Date	Point Rainfall		Maximum 60-min Average Rainfall, mm		
	Maximum	Minimum	Arithmetic	Theissen	Isohyetal
Aug. 17, 1957	69.0	1.1	19.2	23.3	23.2
Sept. 10, 1967*	86.7	4.8	20.7	21.7	21.0
Sept. 10, 1967†	78.9	3.0	20.2	21.3	20.6
Sept. 10, 1967‡	78.9	3.0	16.9	22.4	21.7

*1967 network.
†Without rain gage 52.
‡1957 network.

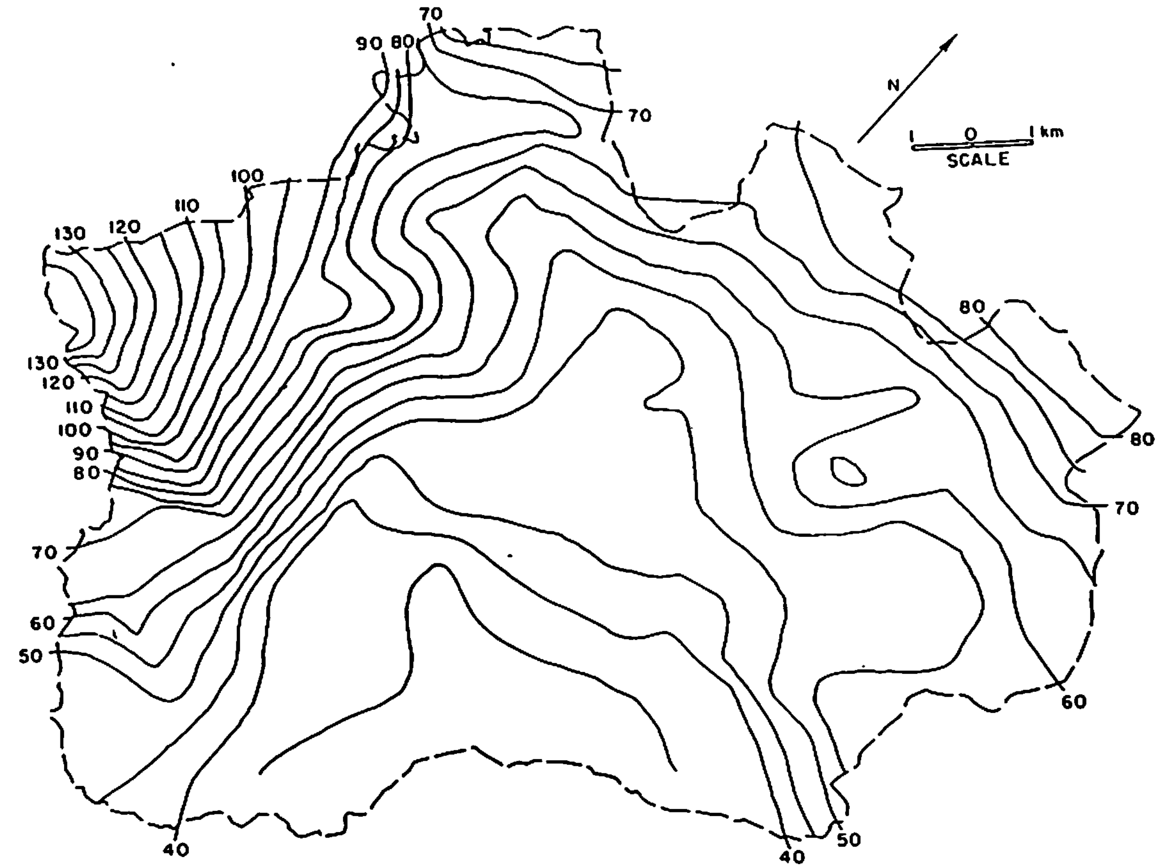


Fig. 8. Maximum 6-hour rainfall (in millimeters), August 21, 1966, Alamogordo Creek.

nated by air mass thunderstorms, gages that are spaced relatively closely in comparison to the national average can be considered independent sampling points for certain situations. For 20 years of record on Walnut Gulch, for example, six gages could be selected that were each separated by at least 6 km ($r \simeq 0.2$). Assuming that the climatic factors leading to air mass thunderstorm development will not change, that the sampling space is homogeneous (negligible effect of elevation

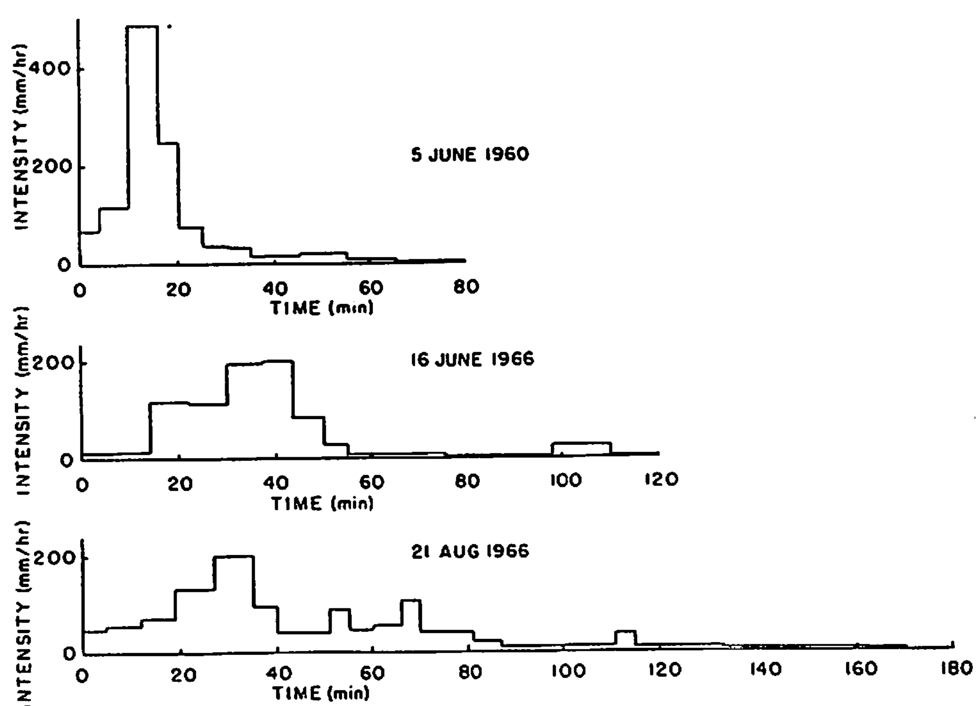


Fig. 9. Rainfall intensity with time for gages recording maximum rainfall for three selected storms on Alamogordo Creek.

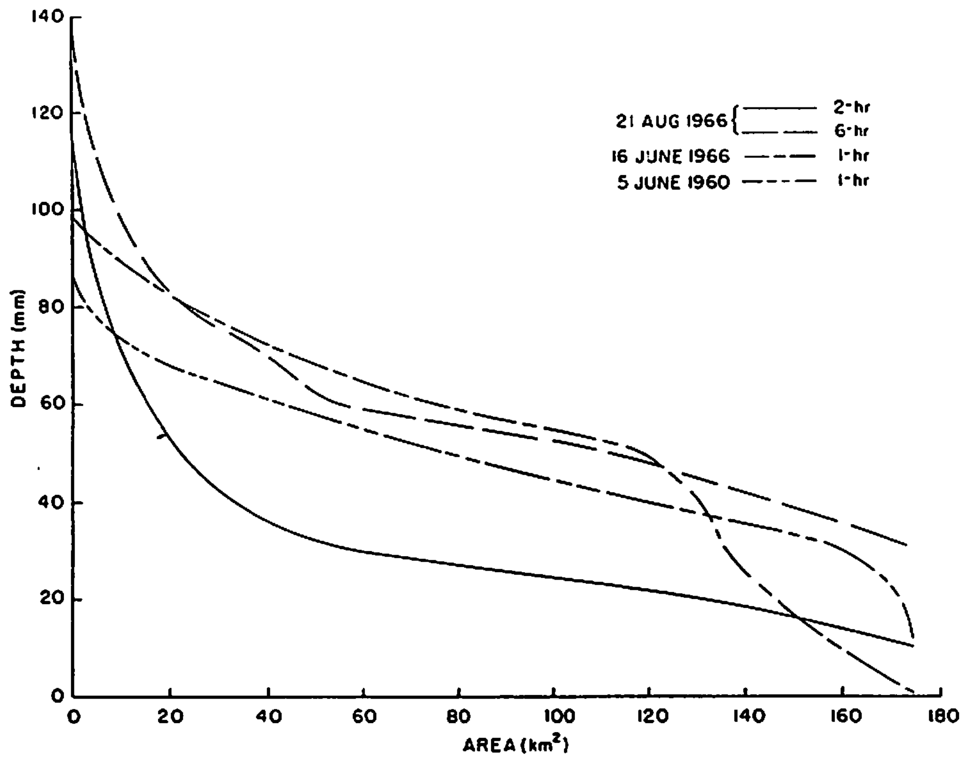


Fig. 10. Depth-area rainfall curves for three storms on Alamogordo Creek.

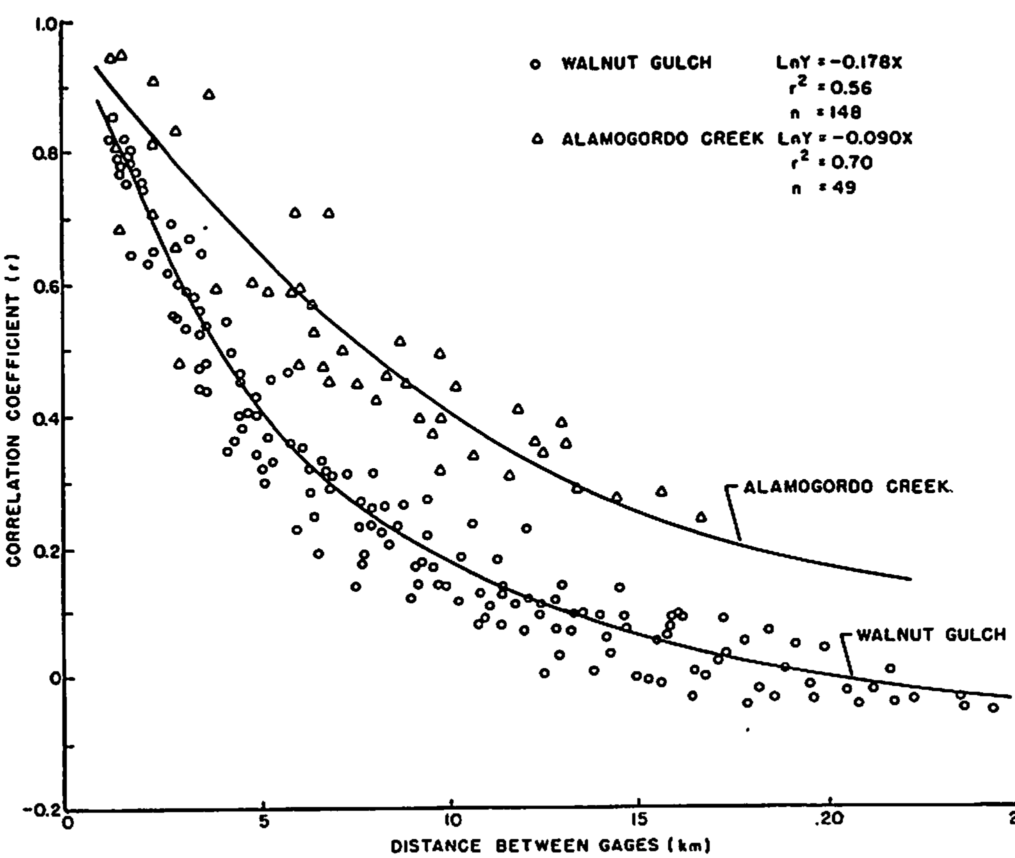


Fig. 11. Correlation coefficients for storm rainfall for selected pairs of gages on Walnut Gulch and Alamogordo Creek.

TABLE 3. Rainfall Prediction From Associated Gages for Maximum 15- and 30-min and Total Storm Rainfall on Walnut Gulch (1957–1976)

	Correlation Coefficient r		
Number of Assocation Gages*	Maximum 15-min Rainfall	Maximum 30-min Rainfall	Total Storm Rainfall
	Central Gage 63.008		
4	0.88	0.94	0.94
1 (1.27 km)	0.75	0.85	0.89
	Central Gage 63.012		
4	0.93	0.95	0.96
1 (1.27 km)	0.88	0.87	0.88
	Central Gage 63.022		
4	0.89	0.92	0.93
1 (0.99 km)	0.82	0.89	0.91
	Central Gage 63.032		
6	0.91	0.92	0.93
3	0.93	0.94	0.94
1 (1.10 km)	0.77	0.82	0.84
	Central Gage 63.052		
7	0.95	0.95	0.95
4	0.94	0.96	0.96
1 (0.86 km)	0.78	0.80	0.77

*The single gage is that nearest the base gage.

and topography), and that the six gages are independent sampling points for maximum rainfall amounts up to 1 hour, the network would be equivalent to a 120-year record.

This hypothesis was tested by selecting such a network for 20 years of record on Walnut Gulch. Each gage recorded maximum annual point values on different dates. Although not entirely conclusive, this certainly supports the hypothesis that for southeastern Arizona, relatively closely spaced gages can be assumed to be independent sampling points for estimates of extreme rainfalls of up to 1-hour duration.

On Alamogordo Creek there is more interdependence between gages for the large frontal convective storms. Since these events also produce the point maximums for shorter durations, an independent network such as suggested for Walnut Gulch would consist of two gages at the most. Extending the length of record from 20 to 40 years is probably little better than estimating 40-year expected amounts from several 20-year records. Again, the differences between the exceptional events on Walnut Gulch and Alamogordo Creek are meaningful.

Accuracy of Rainfall Estimates as Input to Hydrologic Models

Rainfall records from several clusters of gages on Walnut Gulch were analyzed as input to hydrologic models. Maximum 15- and 30-min rainfall and storm totals were compared as estimates of input to very small watersheds using either point records at varying distances from the site or estimates based on several surrounding gages.

First, we estimated values for centrally located gages based on several surrounding gages (Table 3). We wanted to know the accuracy of estimated rainfall input to some type of hydrologic model that would be used at that point assuming a gage did and did not exist. The closest gage in each case was about 1 km; the other gages used were within 2 km. We found in these cases and others that an estimate based on three or four gages was as good as or better than one based on more gages. For example, for 15-min maximums, r varied from 0.75 to 0.88 for the estimate based on the closest gage and from 0.88 to 0.95 for that based on three or four gages. Correlations were better for longer durations, as might be expected.

We then looked at a closely spaced three-gage network on a very small (8 ha), extensively instrumented watershed where simple rainfall/runoff relationships had been previously developed. Correlations for associated gages, including gages outside the three-gage network, which were quite high, are shown in Table 4. We felt therefore that any of the three gages (all within 0.3 km of one another) could be used for modeling purposes within the probable accuracy of both input and output.

Next, we estimated peak discharge for a very small watershed (4.5 ha) based on rain gages at varying distances from the watershed. On the basis of rain gage 63.384, which is located within the small watershed,

$$Q_{pr} = 3.4P_{15} - 17.6 \qquad \text{with} \quad r = 0.89 \tag{1}$$

where Q_{pr} is the peak discharge in millimeters per hour and P_{15} is the maximum 15-min rainfall in millimeters. For gages 63.022, 63.021, 63.080, located 1.2, 1.3, and 1.6 km from the watershed, r = 0.77, 0.77, and 0.71, respectively, between predicted and actual discharge values. The correlations were significantly lower for the more distant gages.

Finally, we investigated the variability in the rainfall factor R in the universal soil loss equation (USLE) in relation to relative rain gage and watershed location. The USLE is

$$A = RKLSCP \tag{2}$$

where A is the estimated soil loss and R is the rainfall factor based on rainfall energy and intensity. (The other parameters describe the soil, vegetation, topography, and cultural practices.) Usually, estimates of R are based on isoerodent maps which include the western United States [*Stewart et al.,* 1975]. However, when recording rain gage records are available, *Wischmeier and Smith* [1958] suggested using rainfall energy and rainfall intensity for more accurate estimates of R. In areas dominated by thunderstorm rainfall there may be some question as to the accuracy of such estimates if the recording gage is some distance from the erosion study.

Again, R was estimated from storms occurring on a very small watershed (4.5 ha). Values of R were calculated for runoff-producing storms for a gage located on the watershed as

TABLE 4. Rainfall Prediction Correlations for Maximum 15-min, 30-min, and Total Storm Rainfall for Three Closely Spaced Rain Gages on Walnut Gulch (1964–1976)

	Correlation Coefficient r		
Number of Gages*	Maximum 15-min Rainfall	Maximum 30-min Rainfall	Total Storm Rainfall
	Base Gage 63.384		
4	0.97	0.98	0.99
2	0.97	0.98	0.99
1 (63.083)	0.96	0.98	0.99
	Base Gage 63.386		
4	0.96	0.98	0.99
2	0.97	0.99	0.99
1 (63.083)	0.97	0.99	0.99

*The single gage is that nearest the base gage.

well as three gages which were 1.2, 1.3, and 1.6 km away. Values of R, and therefore A, varied significantly for individual events for different gages, and the average R was significantly greater for the watershed gage than for the gages located 1.2, 1.3 and 1.6 km away. Correlations between the more distant gages and the watershed gage were $r = 0.93$, 0.99, and 0.85, respectively. On the basis of this analysis it seems that for erosion studies on and within a watershed such as Walnut Gulch, recording gages should be no less than 1 km apart or a gage should be located within a 0.5 km of any small subwatershed where erosion is being studied.

SUMMARY

1. Dense rain gage networks are essential for physically based hydrologic models when the runoff results from air mass thunderstorm precipitation.

2. Summer storms in eastern New Mexico where frontal convective thunderstorms occur can have greater areal extent and point rainfall maximums.

3. The simple correlation for total thunderstorm rainfall between pairs of gages decreases very rapidly with increasing distance between the gages. On the basis of the Walnut Gulch and Alamogordo Creek data, for $r = 0.4$ the gages could be 5 and 10 km apart, respectively. For a simple correlation of 0.9 the gages should be 0.9 and 1.3 km apart, respectively, suggesting rain gage networks of 230 and 100 gages, respectively. Gage networks that differentiate from the hypothetical network can lead to serious overestimates or underestimates of the rainfall volume for a given watershed. The isohyetal maps constructed using different networks illustrated the magnitude of the difference at Walnut Gulch.

4. For air mass thunderstorms, relatively closely spaced gages (about 6 km, $r = 02.$, on Walnut Gulch) can be assumed to be independent sampling points for determining recurrence intervals of extreme values.

5. Estimates of the rainfall energy factor R of the universal soil loss equation (USLE) require closer spacing of the gages than does a rainfall estimate alone. Thus for erosion research on small watersheds (10 ha or less) the gage should be within or very near the area.

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(Received December 18, 1978;
revised May 30, 1979;
accepted June 4, 1979.)