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ANALYSIS OF TWO MAJOR RUNOFF-PRODUCING SOUTHWEST THUNDERSTORMS*

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Abstract: The two largest runoff-producing storms for 10 years of records, the first in 1964 and the second in 1967, recorded on the Walnut Gulch Experimental Watershed in southeastern Arizona are analyzed and compared. Both storms were non-frontal thunderstorms which produced peak discharges on the order of 1500 cfs per square mile; in 1964 from a 2000-acre subwatershed, and in 1967 from an 84-acre subwatershed. During the 1967 storm rainfall of 3.35 inches in 45 min was recorded at one point on the watershed. Approximately 18 acre-feet of runoff was produced on the 84-acre subwatershed in the 1967 storm. Runoff-producing rainfall lasted for less than 60 min for both storms. For both storms, runoff per unit area decreased with increasing subwatershed size because of the large transmission losses in the ephemeral channels and because of the limited areal extent of the runoff-producing rainfall.

Introduction

Information regarding maximum amounts and intensities of precipitation and peak rates of runoff from small (100 square miles or less) watersheds in the Southwest is needed for the design of flood control works, retention and detention reservoirs, road drainages, highway culverts, and urban storm drainages. Also, when designing irrigation facilities in the Southwest, it is generally necessary to provide for protection from storm runoff. Such storm data often are not available. In general, recording rain gages are widely scattered and do not provide satisfactory information on thunderstorm rainfall in this area. This paper presents an analysis and comparison of the two largest runoff-producing storms on the Walnut Gulch Experimental Watershed between 1958 and 1968, and provides needed design information for thunderstorm runoff on small watersheds.

The sources of atmospheric moisture in the Southwest vary with the season. In the summer (late June through early September), moisture

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generally moves into southern Arizona from the Gulf of Mexico. The relative positions of a high-pressure ridge over the central Western United States and a low-pressure trough over northern Mexico regulate this flow of moist air. The combination of moist air and intense convective heating forms thunderstorms. These storms which usually occur in the late afternoon or early evening produce the peak discharges and almost all of the surface runoff from small arid and semiarid rangeland watersheds in the Southwest.

Occasionally, usually in late summer or early fall, a tropical storm in the Pacific will force moist air into Arizona from the southwest. Thunderstorms resulting from this atmospheric condition are usually of longer duration and lesser maximum intensity than are the more common summer thunderstorms.

Experimental Watershed

The Walnut Gulch Experimental Watershed of the Agricultural Research Service is located in southeastern Arizona[1]). It encompasses 58 square miles

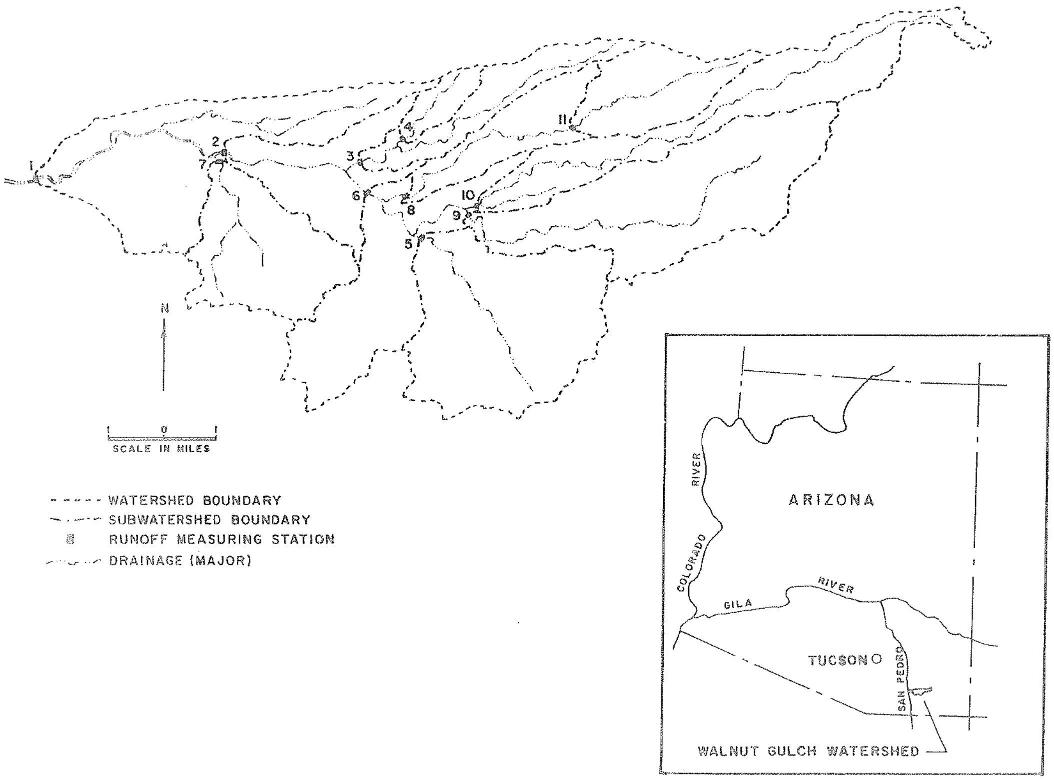

Fig. 1. Walnut Gulch Watershed.

of uncultivated semiarid rangeland around Tombstone, Arizona (Fig. 1). The lower two-thirds of the watershed has mostly a shrub cover, and the upper one-third has mostly a grass cover. Walnut Gulch drains westward into the San Pedro River, which is a tributary of the Gila River.

Precipitation is measured with 93 weighing-type recording rain gages. About 80 of these gages are fairly evenly spaced over the watershed, with the remainder placed either outside the watershed boundary or concentrated on small intensive study areas (Fig. 2).

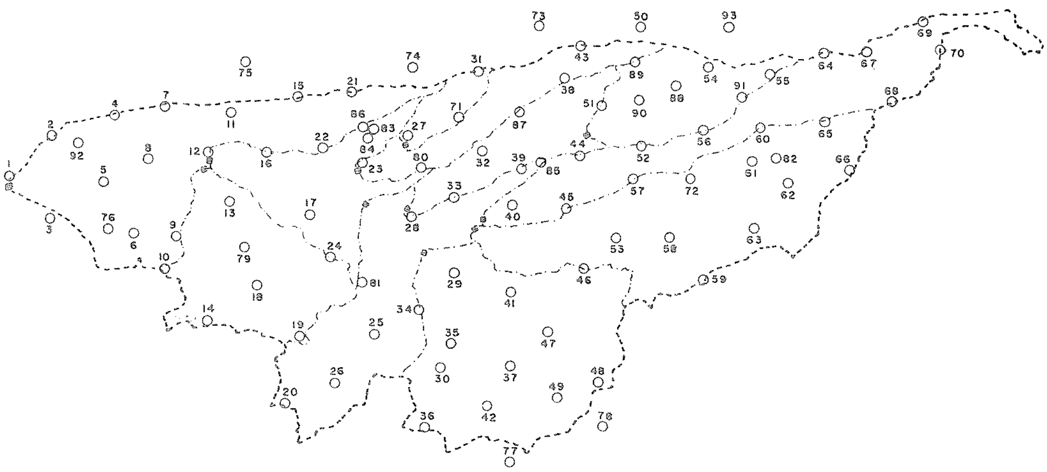

Fig. 2. Walnut Gulch Watershed recording raingage network.

Runoff is measured by combinations of several types of permanent stream-control structures and water-level recorders. Runoff from the nine largest subwatersheds (ranging from 3 square miles to 44 square miles) and from the entire watershed (58 square miles) is calculated from the records of continuous water-level recorders installed in large concrete critical-depth flume-weirs, which are designed especially to measure the flashy runoff from sediment-laden ephemeral streams in the Southwest[2,3]). Runoff volumes from eight subwatersheds ranging in size from 51 to 378 acres are calculated from the records of water-level recorders installed in stock ponds. Runoff from seven smaller subwatersheds, 3 to 120 acres, is determined from water-level recorders located above broad-crested V-notch weirs, and runoff from the two smallest subwatersheds ($\frac{1}{2}$ and 1 acre) is measured by water-level recorders built into 3-foot H-flumes.

On the Walnut Gulch watershed, about 70 percent of the annual precipitation of 11.5 inches occurs during July, August, and September, mostly as thunderstorm rainfall[4]). Except for Subwatershed 5 in the southeastern part of the watershed, rainfall and runoff were well below average in July, August, and the first week in September 1967. Only Subwatershed 5, where several thunderstorms had occurred during the summer months, recorded above-average rainfall in July and August – 9.6 inches, compared to the average of about 7.5 inches.

Precipitation

During the second week of September 1967, the weather of southeastern Arizona was influenced by a tropical storm off Baja California. The U.S. Weather Bureau surface weather map for 13.00 MDT September 10, 1967 shows the location of this storm (Fig. 3). Before this date, moisture had been

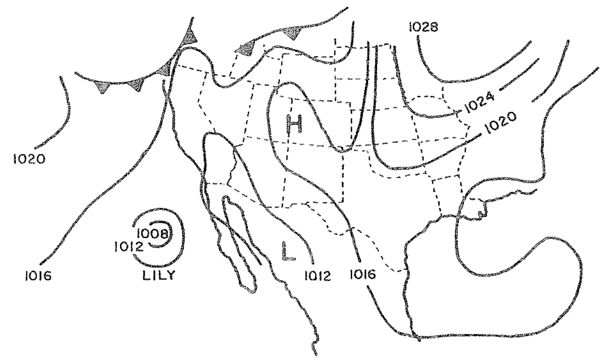

Fig. 3. Surface weather map at 1300 MDT, September 10, 1967.

moving into southeastern Arizona from the Gulf of Mexico along a low-pressure trough extending from northern New Mexico into Arizona. Before 19.00 MDT on September 10, this flow of moist air was cut off by a high pressure ridge (Fig. 4). However, additional moisture carried by winds from the southwest along with the residual atmospheric moisture near the surface, plus high daytime temperatures, made conditions excellent for thunderstorm activity in southern Arizona.

Cumulous clouds began building relatively early in the day on September 10, with some showers recorded on the upper end of the watershed around noon. The early cumulus appeared to dissipate, but by 14.00 hr two separate groups of heavy cumulous clouds were forming, one system just north and one just east of the upper end of the watershed. Some rain was recorded on the north edge of the watershed between 14.00 and 15.00 hr About 15.00, the 2 systems began to move toward each other, and by about 15.15, intense rain was

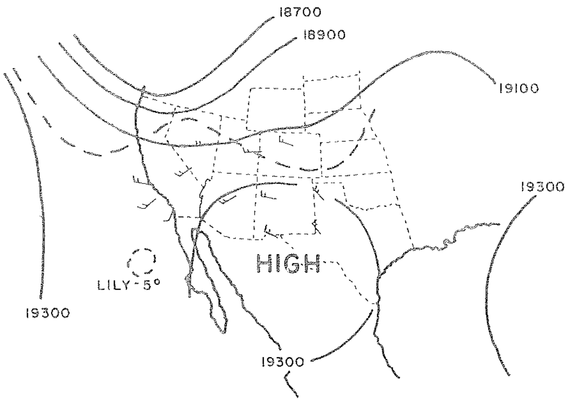

Fig. 4. 500-millibar height contours at 1900 MDT, September 10, 1967.

falling on most of the upper end of the watershed. The two systems combined in the vicinity of Rain Gage 52, and intense rain was recorded there for about 45 min. By 16.00, the storm began to dissipate as well as to move off the watershed to the northwest, and by 16.30, the thunderstorm was over. No hail fell during the storm.

A series of isohyetal maps of precipitation for 10-minute intervals (from 15.00 to 16.10) were drawn to better describe the storm (Figs. 5–11). Between 15.00 and 15.10, significant runoff-producing rainfall (greater than 0.2 inch) was recorded at only one point on the watershed, Rain Gage 43 (Fig. 5).

Fig. 5. Walnut Gulch Watershed isohyetal map. Precipitation (15.00–15.10), September 10, 1967.

From 15.10 to 15.20, heavy rain extended into the upper central portion of the watershed, with roughly 3 square miles of watershed receiving runoff-producing rainfall. Rain Gages 52 and 88 recorded over 0.5 inch in this 10-minute period, and the maximum depth for the period, 0.66 inch (about (4 inches per hour) was recorded at Rain Gage 54, near the northern boundary of the watershed (Fig. 6). There appeared to be three cells within the thunderstorm producing heavy rainfall between 15.10 and 15.20.

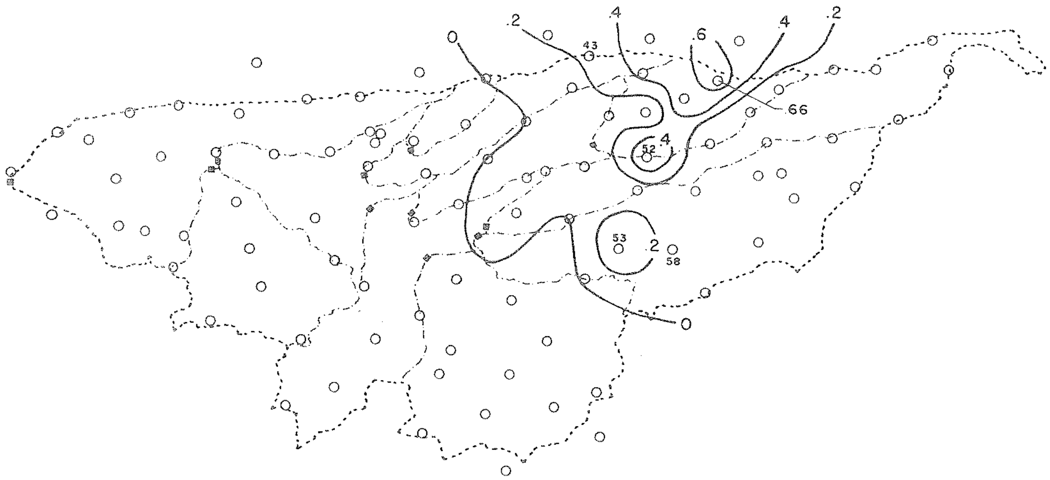

Fig. 6. Walnut Gulch Watershed isohyetal map. Precipitation (15.10–15.20), September 10, 1967.

Fig. 7. Walnut Gulch Watershed isohyetal map. Precipitation (15.20–15.30), September 10, 1967.

Between 15.20 and 15.30, the storm intensified and increased in size as it moved to the southeast. This period was dominated by two major cells, with about 16 square miles of the Walnut Gulch watershed receiving 0.2 inch or more (Fig. 7). Over 0.8 inch of rain was recorded at 4 gages during this period, with a maximum depth of 0.97 inch (5.8 inches per hour) recorded at Rain Gage 58.

From 15.00 to 15.30, the storm had moved slowly to the southeast across the upper central portion of the watershed. The rainfall during this 30-minute period, in itself, was enough to produce appreciable runoff in Walnut Gulch. Normally, such a storm would move off the watershed or dissipate after 20 to 30 min of intense rain. However, about 15.30, new cells developed to the west and northwest, and heavy rain was again on that part of the watershed. Apparently, before 15.30, the rainfall was more strongly influenced by the system of cells that had started developing north of the watershed, whereas after 15.30, the rainfall was more strongly influenced by the system that was building and moving onto the watershed from the southwest. In effect, there were "two events in one." Such events are common, but only very occasionnally develop on a specific watershed to such an extent.

Between 15.30 and 15.40, the storm was centered on much the same area as 20 min earlier. However, both the intensities and the area covered by runoff-producing rainfall were much greater (Fig. 8). Several stations recorded 0.6 to 0.8 inch of rainfall, with 20.4 square miles covered by 0.2-inch or greater rainfall.

The highest intensity of the storm was recorded between 15.40 and 15.50

Fig. 8. Walnut Gulch Watershed isohyetal map. Precipitation (15.30–15.40), September 10, 1967.

when 1.15 inches of rain fell at Rain Gage 44 (6.90 inches per hour) (Fig. 9). During this period, 21.5 square miles were covered with runoff-producing rainfall.

From 15.50 to 16.00, the storm began to dissipate, although about 0.7 inch was recorded at 3 rain gages (Fig. 10), and after 16.00 the rain decreased rapidly as the storm dissipated and moved northwestward off the watershed (Fig. 11). About 10 square miles of watershed received runoff-producing

Fig. 9. Walnut Gulch Watershed isohyetal map. Precipitation (15.40–15.50), September 10, 1967.

Fig. 10. Walnut Gulch Watershed isohyetal map. Precipitation (15.50–16.00), September 10, 1967.

Fig. 11. Walnut Gulch Watershed isohyetal map. Precipitation (16.00–16.10), September 10, 1967.

rainfall from 15.50 to 16.00, and about 4 square miles from 16.00 to 16.10.

At Rain Gage 52, on the upper-central portion of the watershed, intense precipitation was recorded throughout the storm. Stations to the northwest and southeast of this location received considerably heavier precipitation during either the earlier (before 15.30) or the later (after 15.30) period. An isohyetal map of total precipitation (Fig. 12) shows the maximum rainfall

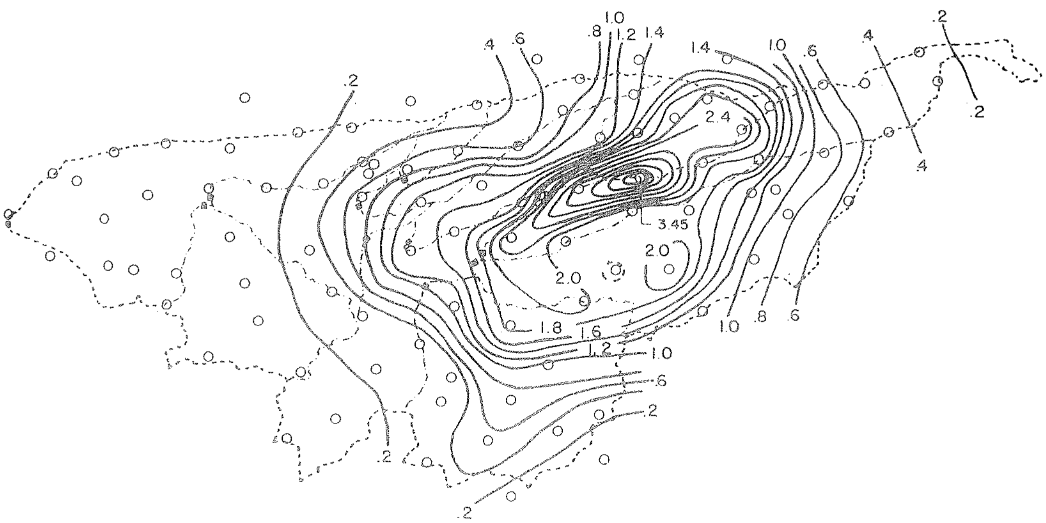

Fig. 12. Walnut Gulch Watershed isohyetal map. Total precipitation, September 10, 1967.

was 3.45 inches at Rain Gage 52. This was the most precipitation recorded at any point on the Walnut Gulch watershed for a duration of one hour or less during the period of record (1956–1967). Of the total amount, 3.35 inches fell in 45 min. At Rain Gage 44, 2.86 inches fell in 45 min, which is about the maximum that we had previously measured on the watershed. Rain Gages 44 and 52 are exactly one mile apart.

The maximum 10-minute depth at each station during the storm was generally higher than that shown for the specific 10-minute periods of the storm. The greatest 10-minute depth was 1.28 inches (7.68 inches per hour) at Rain Gage 44 (Fig. 13). More than one inch in 10 min was recorded at 2

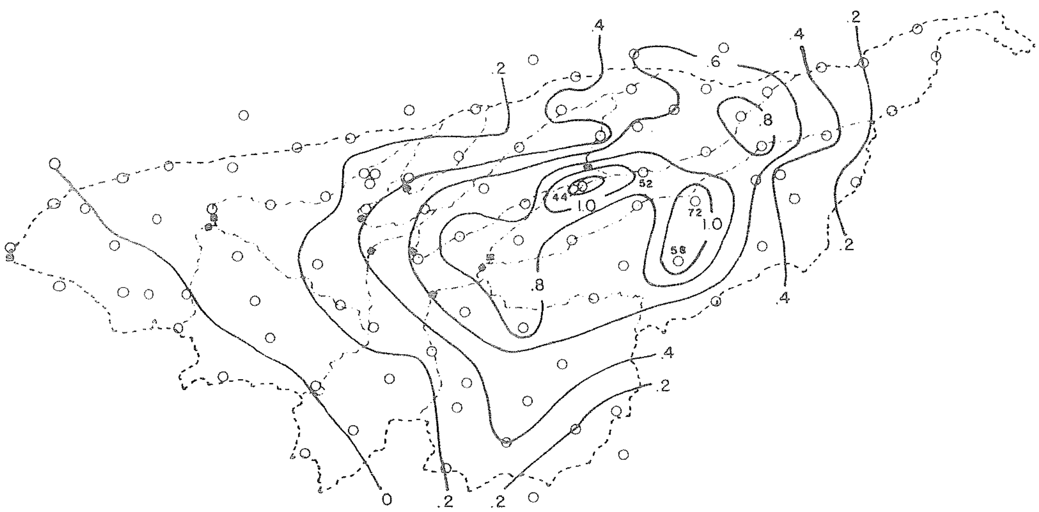

Fig. 13. Walnut Gulch Watershed isohyetal map. Max. 10-min precipitation between (15.20–16.10), September 10, 1967.

other stations, while the maximum at Rain Gage 52 (the storm center), was 0.98 inch (5.86 inches per hour). Higher intensities were recorded for periods of less than 10 min. Again, at Rain Gage 44, the maximum 5-minute intensity was 8.88 inches per hour, and the maximum 4-minute intensity was 9.45 inches per hour. Intensities exceeding 8 inches per hour were also recorded at Rain Gages 52 and 72 for 5-minute periods. Intensities of greater than 8 inches per hour have seldom been recorded on the Walnut Gulch watershed during the 12 years of record.

Depth-area curves were drawn for the total depth of rainfall and the maximum 20-minute depths at each station (independent of when they occurred) (Fig. 14). For comparison, similar curves were plotted on the same

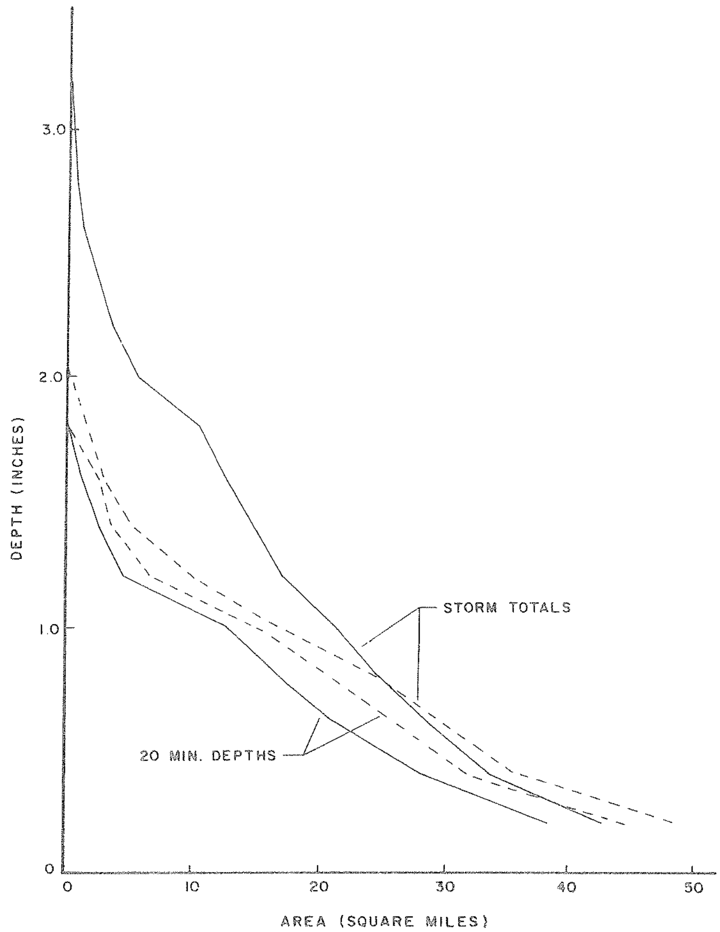

FIGURE 14

Fig. 14. Walnut Gulch Watershed. Depth of precipitation equal to or exceeded vs area.
9/10/67 ————
7/22/64 ---------

figure for a storm on July 22, 1964. Only one storm (August 17, 1957) had higher peak discharges on the main stem than these two during the 12 years of record on Walnut Gulch (1956–1967).

For both the 1964 and 1967 storms, the 20-minute maximum depths exceeded 1.0 inch over more than 10 square miles of the watershed. The 20-minute depths were greater on July 22 than on September 10, but the total rainfall was far greater on September 10 (Figs. 12, 14, and 15). In the 1967 storm, more than 2 inches of rain was recorded at 8 rain gages in less than 50 min.

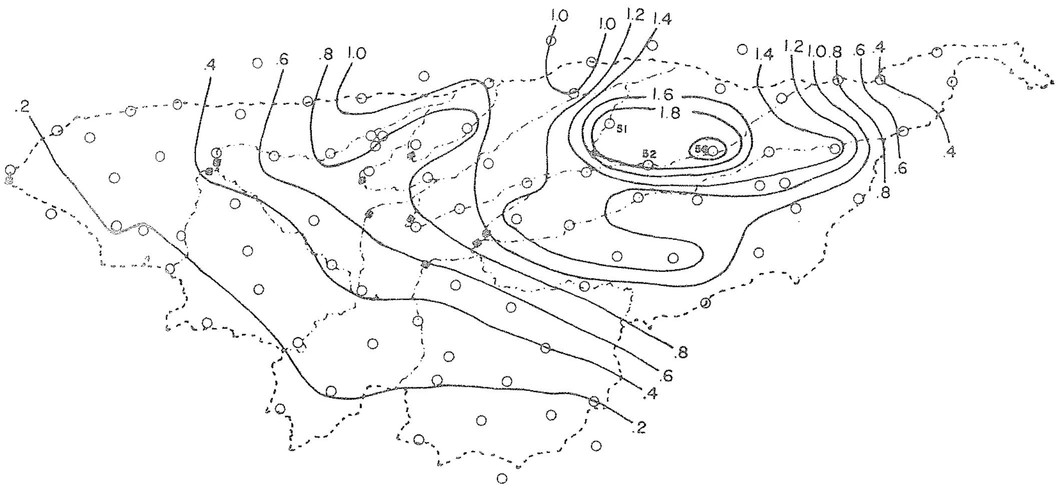

Fig. 15. Walnut Gulch Watershed isohyetal map. Precipitation (18.10–19.10), July 22, 1964.

Actually, the July 22 storm was more typical of thunderstorms in the Southwest. The thunderstorm began developing east of the upper portion of the watershed and reached its peak as it moved across the watershed to the west. The runoff-producing portion lasted less than 30 min. As stated earlier, the storm on September 10 was really "two storms in one," and therefore, produced greater total depths of precipitation than is normally the case. No hail fell during either storm.

Runoff

SMALL SUBWATERSHEDS (LESS THAN 400 ACRES)

As mentioned earlier, the heaviest rainfall on September 10 was in the upper-central portion of Walnut Gulch watershed in the vicinity of Rain Gages 44 and 52. Stock Pond 15, instrumented with a continuous water-level recorder before the 1966 season, is located between Rain Gages 52 and 44 (Fig. 16). This pond, which drains 84 acres and has a capacity of 8.9 acre-feet to spillway level, held less than 1 acre-foot of water before the storm.

As a result of the storm, the pond filled to capacity, and an estimated 10 acre-feet of water overflowed the spillway. Total runoff from the 84-acre subwatershed from 45 min of rainfall was about 18 acre-feet, or 2.6 inches over the area. This volume of runoff per unit area was about twice what we had measured from any previous storm on any gaged watershed on Walnut Gulch. With only seven years, or less, of record from the small subwatersheds

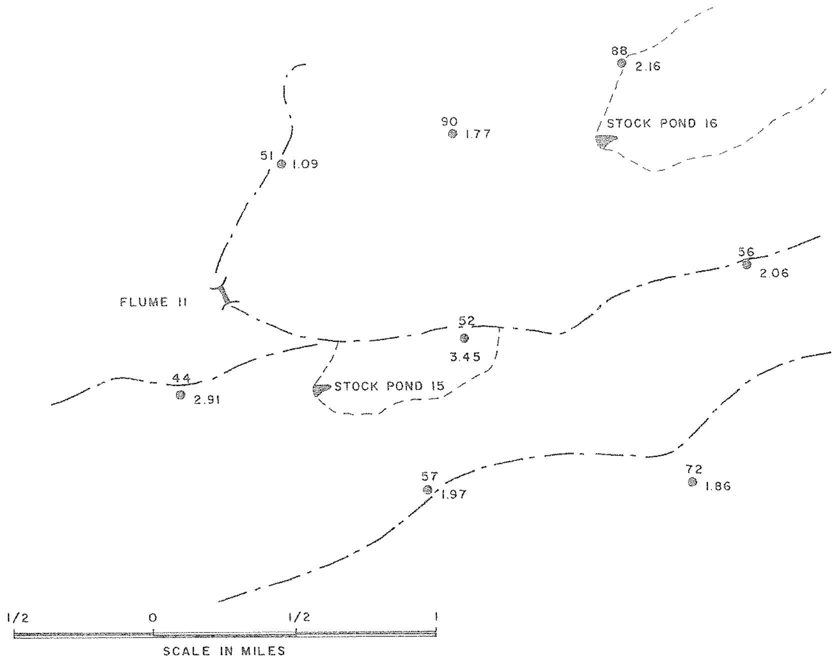

Fig. 16. Walnut Gulch Experimental Watershed. Stock Pond 15 and vicinity. Precipitation (inches), September 10, 1967.

(350 acres and less), it is difficult to estimate even roughly with what frequency a storm of this magnitude could be expected on a specific 84-acre subwatershed, but it would be expected probably more often than once in 100 years. Also, on the basis of the relatively short period of record at Walnut Gulch (12 years), a 3.4-inch, 45-minute point rainfall can be expected on some part of the 58-square-mile watershed on the order, roughly, of once every 10 years, and at a specific point, probably more on the order of once every 50 to 100 years.

Although water-level recorders provide a good record of runoff volumes into stock ponds, they do not provide a good record of rates of runoff. On September 10 at Stock Pond 15, however, the peak discharge apparently occurred or was still occurring after the pond had filled, and the peak rates of inflow and outflow occurred almost simultaneously. It was estimated, both from the spillway geometry and the pond capacity above spillway level, that the peak discharge was at least 200 cfs, or better than 1500 cfs per square mile.

Because of the long duration of the storm (on September 10, 1967), the estimated runoff hydrograph had a very broad peak. We have twice recorded peak rates of about 1500 cfs per square mile on the Walnut Gulch watershed, but the thunderstorms that produced these two flows lasted only about half as long and produced sharp, rather than broad, hydrograph peaks.

LARGE SUBWATERSHEDS (MORE THAN 400 ACRES)

Hydrographs for the September 10, 1967 event at Flumes 11, 8, 6, and 1 are shown in Fig. 17. These structures measure runoff from 3.2-, 6.0-, 36.7-, and 57.7-square-mile watersheds, respectively. Flume 8 measures runoff from about one-sixth of the total drainage above Flume 6. The three peaks at Flume 6 (the uppermost flume on the main channel) resulted primarily from runoff from three of the major subwatersheds above this flume and from the

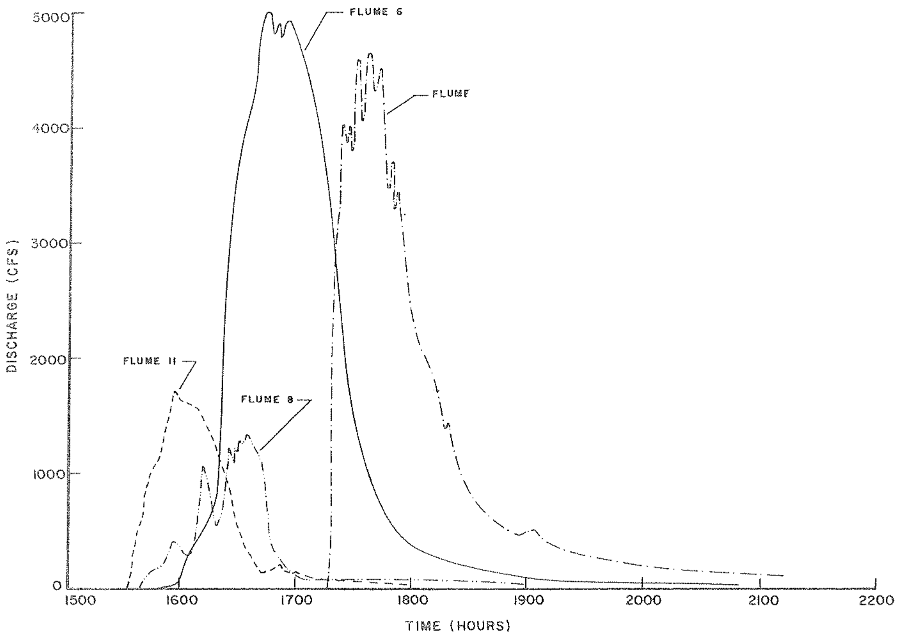

Fig. 17. Walnut Gulch Experimental Watershed. Hydrographs for storm of September 10, 1967.

different periods of intensity within the storm. These within-storm intensity differences are reflected in the Flume 8 hydrograph.

The 5010-cubic-foot-per-second peak discharge at Flume 6 for this flow is the second largest peak for the period of record (1962 to present). It has been exceeded only by a peak of 7340 cfs on July 22, 1964. Both events, however, produced nearly the same volume of runoff – 430 acre-feet at Flume 6.

The hydrographs for the July 22, 1964 event at Flumes 11, 8, 6, and 1 are shown in Fig. 18. All runoff-producing precipitation for both this event and the September 10, 1967 event fell within Subwatershed 6. Differences in precipitation characteristics probably caused most of the differences between the hydrograph shapes at Flume 6.

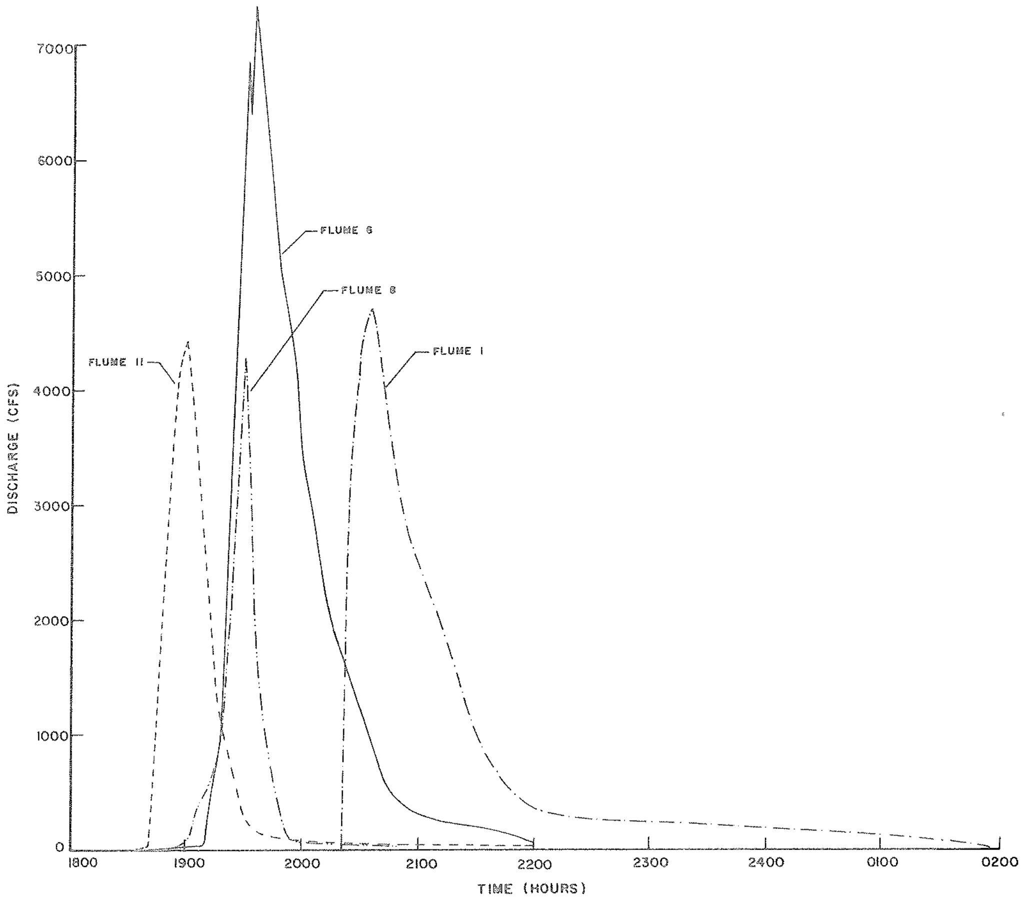

Fig. 18. Walnut Fulch Experimental Watershed. Hydrographs for storm of July 22, 1964

Figure 19 shows, for both storms, the volume of precipitation above a given isohyet for the storm total and for the maximum 20-minute intensity in the storm. The September 10 storm, as explained previously, was of longer duration and was actually two convective systems moving together with resulting high precipitation totals from the longer duration. The July 22 storm actually had only $\frac{1}{3}$ the volume of rain above the 1.0-inch isohyet as

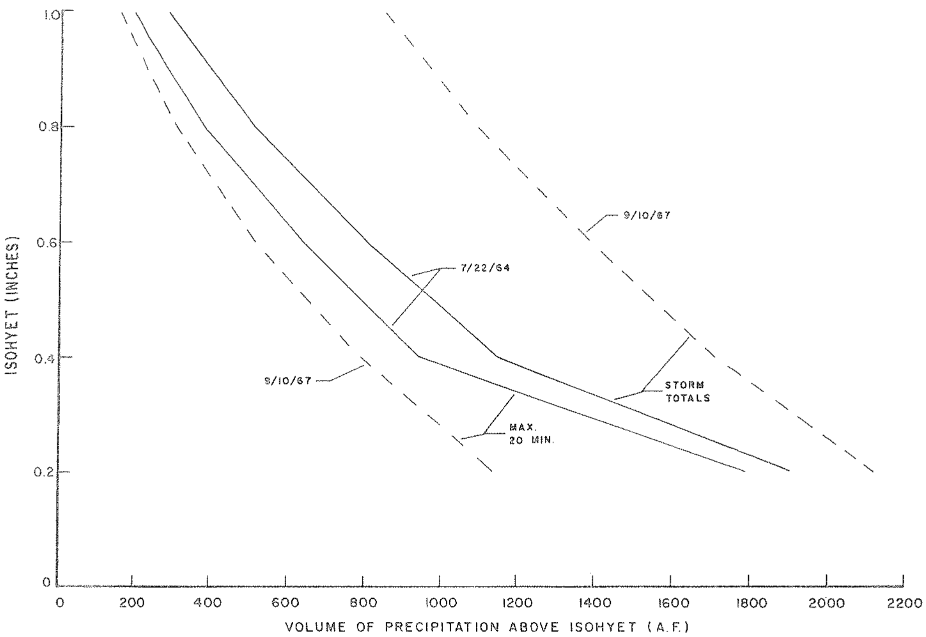

Fig. 19. Volume of precipitation above isohyet depths for storms of Sept. 10, 1967 and July 22, 1964.

did the September 10 storm. The longer duration of rainfall on September 10, therefore, allowed greater infiltration, while generating nearly equal amounts of "on-site" runoff to those for the July 22 storm.

Relatively dry periods preceded both flow events. The July 22 event, which was early in the flow season, had been preceded by very small flows in the main stem of Walnut Gulch (between Flumes 6 and 1) on July 12, 18, and 20. The channel was also relatively dry for the flow of September 10, 1967, with only two very small flows occurring between August 3 and September 10.

Braided flow can occur in many channel segments on the lower portion of the watershed. Such flows form islands, some with vegetation. When discharges exceed 2,000 cfs, most of these islands are flooded during part of the flow. The increased surface that is flooded permits correspondingly higher transmission losses. The July 22 flow, with its higher peak discharge at the upper end of the channel, inundated many of these islands. Thus, the July 22 peak discharge of 7340 cfs at Flume 6 was reduced to 4700 cfs at Flume 1, and 87 acre-feet were lost by transmission losses (429 acre-feet at Flume 6 to 342 acre-feet at Flume 1). The peak discharge attenuation for September 10 was from 5010 cfs at Flume 6 to 4670 cfs at Flume 1, with 68 acre-feet of transmission losses.

Over 80 percent of the 1967 runoff on the main stem of Walnut Gulch resulted from the September 10 storm that amounted to less than 15 percent of the total volume of summer rainfall. When the peaks and volumes of runoff at Stations 11, 8, 6, and 1 on September 10 are compared with the peaks and volumes of the second largest runoffs in 1967, as well as to the total runoff in 1967 and the total runoff in 1965, 1966, and 1967, the relative importance of such major storms can be seen more clearly (Table 1). For

TABLE 1

Runoff peak and volume – Walnut Gulch Experimental Watershed

Subwatershed number	1	6	8	11
Watershed area (square miles)	57.7	36.7	6.0	3.2
1967 maximum peak discharge (cfs)	4700.	5000.	1500.	1700.
1967 second highest peak discharge (cfs)	240.	730.	97.	261.
Max. peak discharge for period of record (cfs)	*11,500.	**7300.	**4300.	**4400.
1967 Max. storm volume (acre-feet)	350.	430.	75.	107.
1967 second largest storm volume (acre-feet)	48.	52.	3.	11.
1967 runoff (acre-feet)	425.	520.	83.	125.
1965–66–67 runoff (acre-feet)	800.	1110.	230.	270.

* August 17, 1957.
** July 22, 1964.

example, the peak discharge in 1967 at Flume 6 was about 7 times as great as the peak discharge from the second largest runoff event, and the maximum peak discharge at Flume 1 was about 20 times that of the peak discharge for the second largest event. From about $\frac{1}{3}$ to $\frac{1}{2}$ of the total runoff in 1965, 1966, and 1967 at the four stations occurred on September 10. Obviously, the exceptional events are extremely important in studies of water yield and sediment transport as well as for flood design purposes.

Runoff Prediction

The development of rainfall-runoff relationships from small watershed data is generally difficult. An example of the problems encountered can be shown from the record on the 3.2-square-mile Subwatershed 11 for these two flow events. The average depths of rainfall on this subwatershed were 2.05 inches and 1.80 inches for the storms of September 10, 1967 and July 22, 1964, respectively. The September 10 storm, however, represented about a 60-minute duration of runoff-producing rainfall, whereas the runoff-producing portion on the July 22 storm was only about 30 min long. The hydrographs of these two storms on Subwatershed 11 differ tremendously (Figs. 17 and 18). A peak discharge of 4400 cfs, with 159 acre-feet of runoff (0.939 inches), occurred from the July 22 storm. The peak discharge for the September 10 storm was 1700 cfs with 107 acre-feet of runoff (0.633 inches). The differences in the hydrographs at Flume 11 are attributable primarily to differences in intensity in the storms. Volumes of runoff at Flume 11 amounted to 50 percent and 30 percent, respectively, of the runoff-producing rainfall on July 22 and September 10.

The relationships of peak discharge per square mile and runoff volume per square mile to drainage area are plotted for W-11, W-8, W-6, and W-1 (Fig. 20). Also, the value of runoff on September 10 at Pond 15 is shown. The best fit lines, drawn by eye, are quite different for the two storms, except for the larger sized watersheds, W-6 and W-1. If the data are extrapolated, the values of peak and volume on a 1-square-mile watershed are 4000 cfs and 90 acre-feet, and 800 cfs and 45 acre-feet, from the July 22 and September 10 storms, respectively. For comparison, we have measured a peak of 1400 cfs and a volume of 60 acre-feet from a single storm on a 550-acre subwatershed on Walnut Gulch.

The negative slope for the lines in Fig. 20 reflects the effect of a convective thunderstorm with less than all of the watershed area contributing runoff, as well as the effect of transmission losses. When the convective storm producing runoff covers less than the total area and when flow is in an ephemeral stream with a highly previous streambed, both the hydrograph peak per unit area and the runoff volume per unit area tend to decrease with increasing watershed size.

Records of accurate measurements of both precipitation and runoff from thunderstorms on rangeland watersheds in the Southwest are hard to find. In one such record, the U.S.G.S. reported a peak discharge of 9500 cfs (1400 cfs per square mile) from a 6.67-square-mile drainage in southwestern New Mexico near Socorro on August 1, 1956[5]) which compares closely to the maximum peaks we have measured on our 1- and 3-square-mile subwatersheds. The Socorro flood was referred to by a resident as "the worst flood which he had seen at the site since a similar but somewhat greater flood which occurred 60 years previously." No rainfall information was available.

Peak discharges in the Southwest in the neighborhood of 1500 cfs per

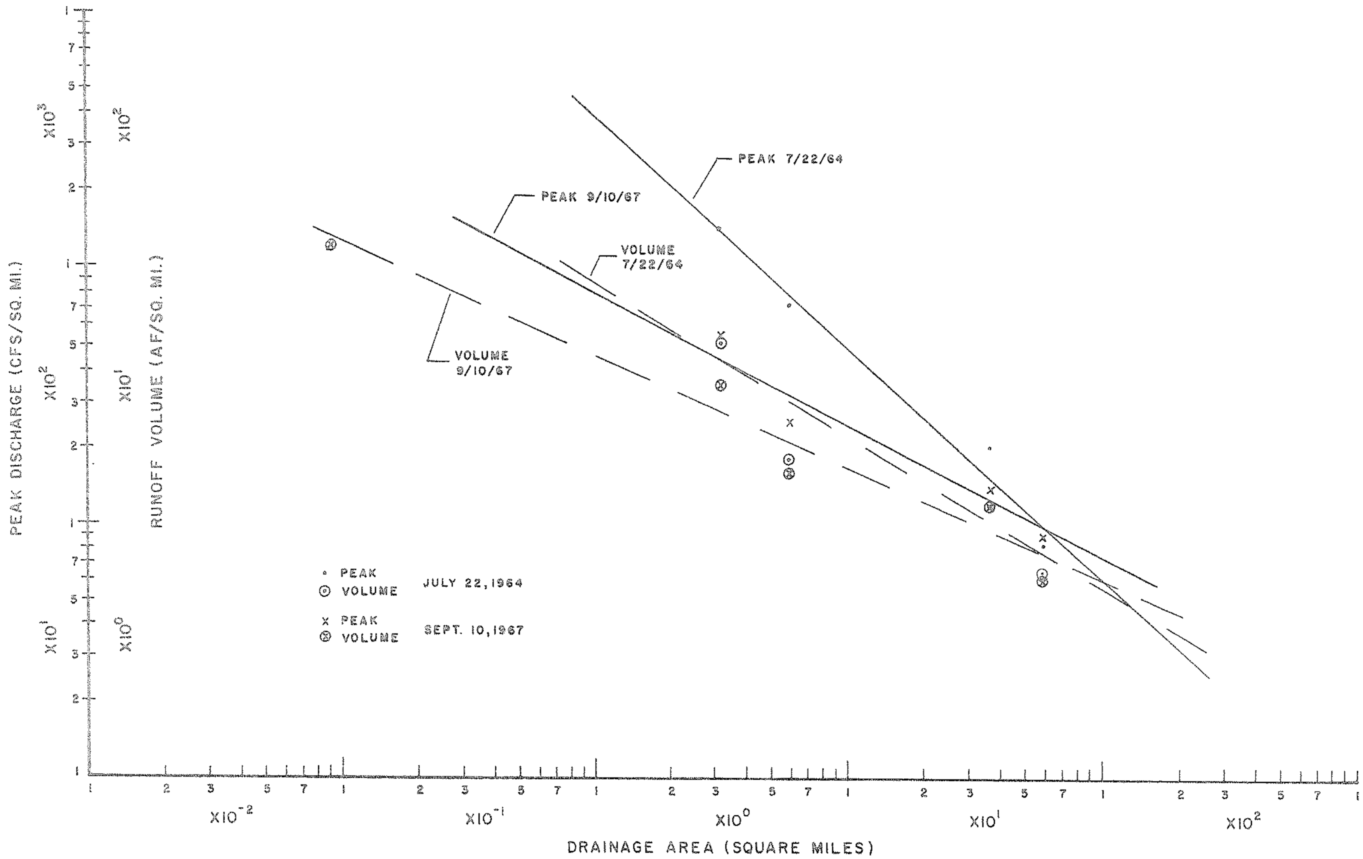

Fig. 20. Walnut Gulch Experimental Watershed. Discharge versus area.

square mile have been estimated by the U.S.G.S. on a few occasions in the past 65 years. However, as far as we know, two such peaks have never been officially measured on any watershed in the Southwest.

Conclusions

The following observations and preliminary conclusions are made from the *relatively short* period of precipitation and runoff records obtained on the Walnut Gulch Experimental Watershed.

(a) A peak discharge on the order of 1500 cfs per square mile has been measured three times, once each on subwatersheds of 84, 550, and 2000 acres.

(b) A peak rate of discharge of 1500 cfs per square mile probably occurs on some part of the principal watershed several times in 10 years. However, such an event on a specific small subwatershed would be expected less than once in 10 years, and probably closer to once in 50 years.

(c) On an 84-acre subwatershed, one thunderstorm lasting less than one hour produced 18 acre-feet (2.6. inches) of runoff, which was about 75 percent of the storm rainfall. Runoff per unit area from this 84-acre drainage (137 acre-feet per square mile) was more than twice that measured on any other subwatershed during the period of record.

(d) Runoff approaching 130 acre-feet per square mile for a 100-acre, or less, subwatershed may occur on some part of the principal watershed about once every 10 years, but on a specific small subwatershed, probably no more often than once in 100 years.

(e) The maximum one-hour point rainfall was 3.45 inches with 3.35 inches measured in 45 min. Just under 3 inches of rainfall have been measured in one hour on several occasions.

(f) An hourly 3.45-inch rainfall should be recorded at some point on the principal watershed on the order of once every 10 years; an hourly 3.45-inch rainfall should be expected at a given point more on the order of once in 100 years.

(g) Individual exceptional storms produce as much surface runoff as several years of normal runoff. Such storms also provide the unusual peak discharges and storm volumes needed for flood design purposes.

(h) Average annual runoff per unit area decreases as watershed size increases because of transmission losses in the permeable alluvial streambeds.

(i) Storm runoff per unit area decreases as watershed size increases because of the limited areal extent of runoff-producing thunderstorms and because of the transmission loss in the streambeds.

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