Model of Time and Space Distribution of Rainfall in Arizona and New Mexico

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ABSTRACT

Rainfall data from two dense rain gage networks, several small groups of rain gages, and National Weather Service (NWS) rain gages are used to describe the occurrence and depth-area distribution of rainfall and to develop a rainfall simulation program (model) for Arizona and New Mexico. Depth-area rainfall distribution is described by an assumed cellular thunderstorm structure, with verification limited to comparison of simulated and actual total rainfall patterns. Simulated rainfall is convenient to use in hydrologic models when long term rainfall records are unavailable. If point records are available, they can be used to verify the model.

The program output includes accumulated seasonal rainfall for any designated point (gage), point totals for individual events for isohyetal mapping, starting and ending times for all events, and Thiessen weighted watershed averages. The output can be used directly to estimate peaks and volumes of runoff for very small watersheds (up to 100 hectares), and indirectly for larger watersheds with appropriate routing methods. Since the rainfall is distributed both in time and space, simulations of several years of record could be used to provide probabilities of wet and dry sequences to evaluate the chances of success for range renovation programs and could aid ranchers in overall planning of range management programs.

KEYWORDS: Rainfall, hydrology, model, semiarid, simulation, precipitation, thunderstorm, rain gage, range, watershed, computer.

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MODEL OF TIME AND SPACE DISTRIBUTION OF RAINFALL IN ARIZONA AND NEW MEXICO

By H. B. Osborn, E. D. Shirley, D. R. Davis, and R. B. Koehler

INTRODUCTION

Rainfall is an input used in most hydrologic models that estimate runoff mes or peak discharge. Simulated rainfall is convenient to use in the lopment of such models because long and complete precipitation records, cal of areas where the model is to be applied, can be quickly generated. lated rainfall is necessary in applying such models to areas where rain s are scarce or nonexistent or where historical records are too short. e one or more point records are available, they can be used to verify models o manipulate parameters in the models.

In this paper, rainfall data from two dense rain gage networks, several l groups of rain gages (fig. 1), and National Weather Service (NWS) rain s are used to develop a rainfall simulation program for Arizona, New Mexico, similar semiarid regions. We first describe the rainfall occurring in these s and then present a simulation program involving several rainfall models. ologic assumptions and simplifications in the program subroutines are dis- ed, and sample program output is described.

SELECTED RELATED RAINFALL STUDIES

Osborn and Lane (*1969*) studied the relative sensitivity of rainfall vari- s and watershed characteristics on runoff from intense, short-duration derstorm rains. They found that, for four very small watersheds (4 ha and), runoff volume was most strongly correlated to total rainfall and peak harge was best correlated to maximum 15-min rainfall. Total runoff was also ıly correlated to maximum 15-min rainfall, because the maximum 15-min rain-

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The year in italic, when it follows the author's name, refers to Litera- Cited, p. 21.

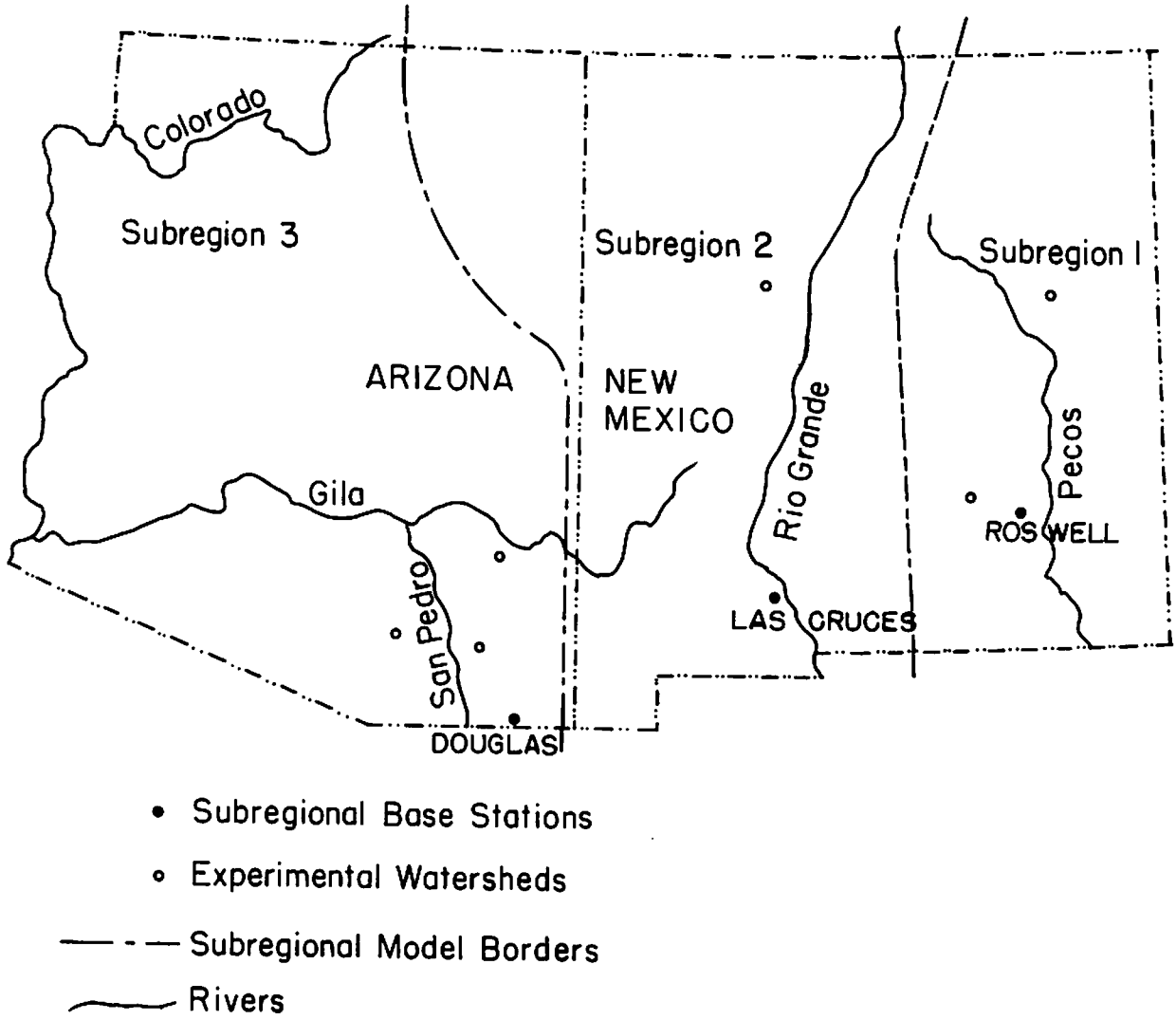


Figure 1.--Region and subregions covered by regional rainfall model.

ıll is usually related to storm total. Rainfall dominated the relationships. :ffering watershed characteristics did not add significantly to estimates of :aks or volumes of runoff, but the watersheds studied were quite similar.

Fogel (*1969*) reported on the effects of storm rainfall variability on run- f from small watersheds in the Southwest. He pointed out that runoff is a mplicated process and becomes more complicated when the input is highly in- nse, short-duration thunderstorm rainfall of limited areal extent. Most cur- nt methods for estimating runoff volumes require knowledge of only total rain- ll depth, which can lead to significant errors in estimating runoff.

Duckstein et al. (*1972*) introduced a stochastic model of runoff-producing infall for summer-type storms in the southwestern United States. They pointed t that modifications in runoff can occur either naturally or through human in- uences, and that in either case rainfall input must be properly modeled to de-

mine actual changes in runoff with changes in watershed characteristics. y consider summer rainfall as an intermittent stochastic phenomenon and ob- ned the probability distribution of areal rainfall by convoluting a Poisson tribution for the number of events with a geometric or negative binomial pro- ility of rainfall amount. They then used their rainfall model in several nfall-runoff relationships to illustrate the practical value of the method.

Osborn and Laursen (*1973*) identified the differences in the runoff-pro- ing characteristics of the airmass thunderstorms common to Arizona and west- New Mexico and the frontal convective rains more common to eastern New ico and western Texas. They found that peak discharge from semiarid range- d wastersheds larger than 2 km^2 in southeastern Arizona was best correlated maximum 30-min rainfall (as opposed to maximum 15-min rainfall for very small ersheds), which they referred to as the core of runoff-producing thunderstorm nfall. The simulation program presented in this paper is based on the con- t of a core of runoff-producing rainfall and can be used for watersheds of m^2 and larger.

RAINFALL DEPTH-AREA DURATION

The USDA Southwest Rangeland Watershed Research Center (SRWRC) has operated 150-km^2 Walnut Gulch Experimental Watershed in southeastern Arizona and the -km^2 Alamogordo Creek Experimental Watershed in eastern New Mexico since 1954 g. 1). Currently, there are about 95 and 65 recording rain gages, respec- ely, on the two watersheds, although not all of the gages have been operated ing the full period of record. Also, the SRWRC operated several small exper- ntal watersheds near Safford, Ariz., and Albuquerque, N. Mex., through 1976, near Ft. Stanton, N. Mex., from 1966 to the present. Data collected from se networks are used to illustrate the range and variability of runoff-pro- ing characteristics of thunderstorm rainfall.

Regional differences in rainfall amounts and intensities in arid and semi- d regions have been widely investigated; however, quantitative descriptions these differences, usually as depth-duration frequencies, generally have ored differences in the storm system that generated the rainfall, and have ped together essentially different storm populations. For example, thunder- rm rainfall occurring in the arid and semiarid regions of the Southwest can divided roughly into rains occurring from airmass thunderstorms and from ntal-convective thunderstorms.

Differences in runoff-producing characteristics between and within the two nderstorm types--airmass and frontal-convective--are best illustrated using a from dense rain gage networks on the Walnut Gulch and Alamogordo Creek ersheds.

Airmass Thunderstorms

The extreme spatial variability of airmass thunderstorms, which is typical southeastern Arizona, is illustrated by an isohyetal map of total storm rain-

fall for the event with the maximum 1-hr rainfall on Walnut Gulch (fig. 2). Maximum observed point rainfall was 88 mm, with depths decreasing rapidly, but unevenly, from the maximum point. All surrounding gages recorded less than 70 mm of rainfall. An area of less than 2 km^2 received more than 70 mm of rainfall. In one direction, depths were less than 25 mm within 3 km of the maximum.

The durations of runoff-producing thunderstorm rains are also extremely variable. For example, for the storm of September 10, 1967, rainfall lasted up to 70 min at some gages, but only 45 min at the storm center. Intense rainfall usually lasts for less than 20 min at any one gage. The major events last longer than the smaller events, but do not necessarily have greater intensities.

Many rainfall-runoff relationships are based on average rainfall for a given duration. Amounts for shorter durations are derived by multiplying the longer duration amount by some given fraction. The recommended fractions are often based on average storm values, which may be misleading for design purposes for the major more infrequent events. Ratios of rainfall depths for short duration to 1-hr amounts for 37 events of 25 mm or more on Walnut Gulch are shown in table 1. The average ratio of 15-min and 30-min depths to 1-hr depths are 0.66 and 0.88, respectively, for the 37 storms, but only 0.41 and 0.72, respectively, for the record maximum 1-hr event. If, for example, the 1-hr, 100-yr maximum point rainfall was 88 mm, the 30-min rainfall based on an average value of 0.88 would be 77 mm rather than 62 mm. The two values entered into the same rainfall-runoff model would give significantly different estimates of the 100-yr peak discharge. Whereas average or generalized values might be acceptable, on the average, for runoff design for the more common events, they might lead to overestimates of rainfall for individual events.

Table 1.--*Ratio of storm rainfall depth for various durations to 1-hr rainfall for 37 storms of greater than 25 mm for Walnut Gulch.*

	Duration (min)					
	5	10	15	20	30	60
Average	0.28	0.50	0.66	0.76	0.88	1.0
Range	0.15-0.54	0.28-0.77	0.38-0.92	0.47-0.96	0.66-1.0	---
Sept. 10, 1967[1]	0.17	0.31	0.41	0.53	0.72	1.0

[1]Maximum 1-hr point rainfall (88 mm); the only measured 1-hr amount greater than 75 mm on Walnut Gulch (1955-77).

Depth-area curves for maximum 1-hr rainfall for the storms of September 10, 1967, July 22, 1964, and August 17, 1957, on Walnut Gulch (dashed lines in lower portion of fig. 3) again illustrate the limited areal extent of airmass thunderstorm rainfall.

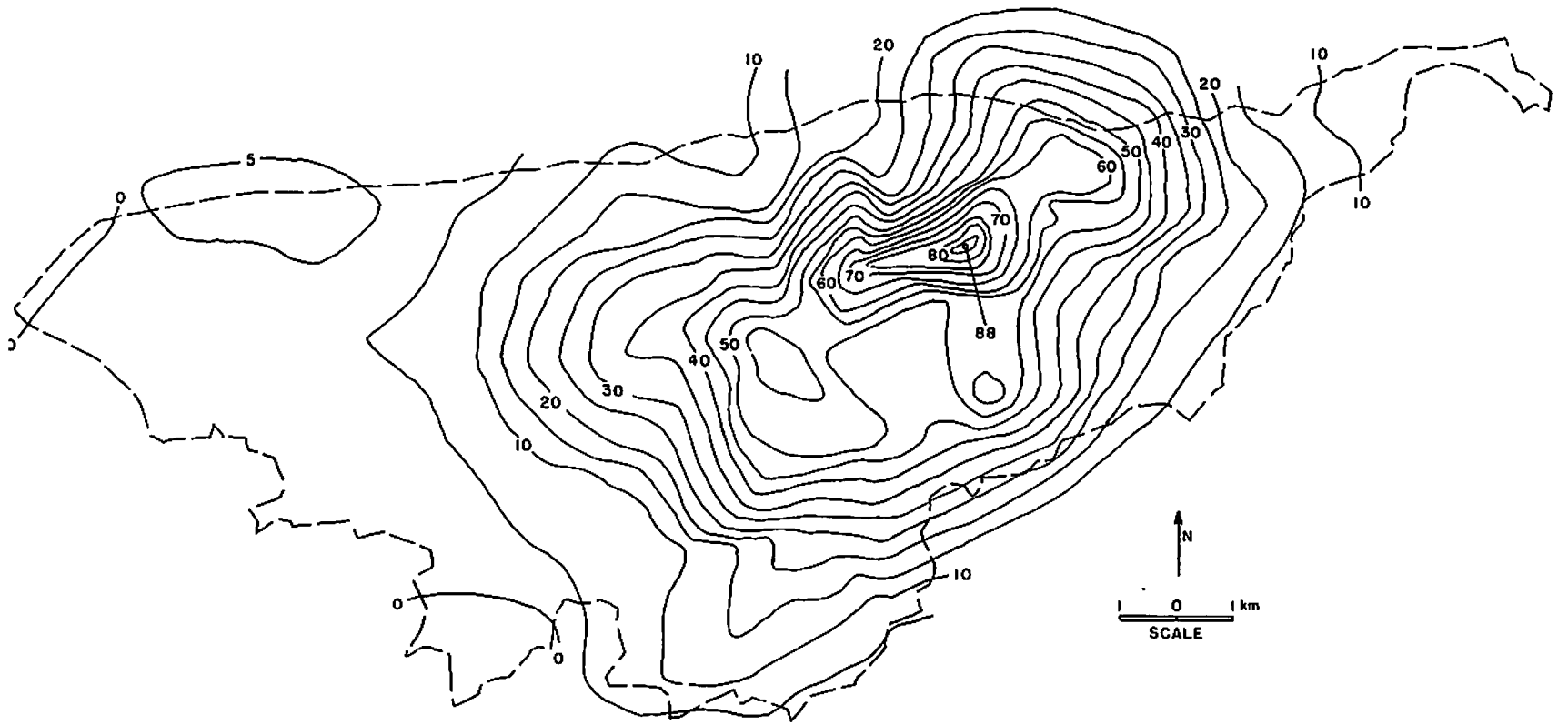
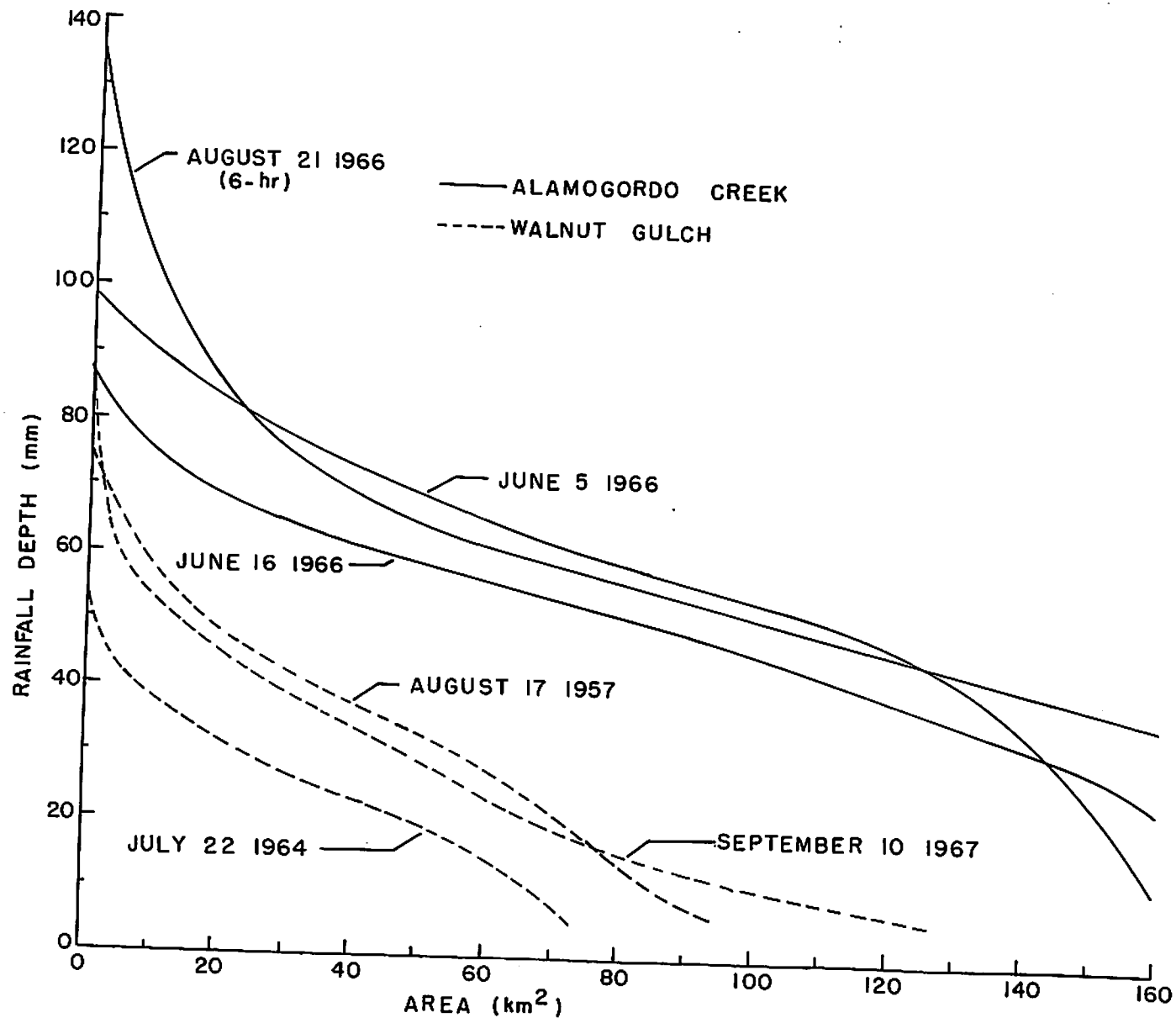


Figure 2.--Isohyetal storm rainfall map of September 10, 1967, Walnut Gulch. Each contour represents 5 mm of rainfall.


140
120
100
80
60
40
20
0
RAINFALL DEPTH (mm)
0
20
40
60
80
100
120
140
160
AREA (km²)
AUGUST 21 1966
(6-hr)
ALAMOGORDO CREEK
WALNUT GULCH
JUNE 5 1966
JUNE 16 1966
AUGUST 17 1957
JULY 22 1964
SEPTEMBER 10 1967

Frontal Convective Thunderstorms

Frontal-convective thunderstorms, which are common in eastern New Mexico, n cover more area, last longer, and produce greater amounts of rainfall for milar durations than airmass thunderstorms. The more massive nature of some ontal-convective thunderstorms is illustrated by an isohyetal map of total orm rainfall for the event with the maximum recorded 1-hr rainfall on Alamo-rdo Creek (fig. 4). Rainfall ranged from 4 mm to 103 mm, with four gages cording 100 mm of rain or more. Almost all rain fell in 1 hr. Although the orm was more massive than an airmass thunderstorm, it was reasonably well ntered on the watershed, and apparently extended for only short distances out-de the watershed. Unfortunately, the network was not large enough to encom-ss the entire storm.

Ratios of rainfall depths for short durations (up to 1 hr) for 37 airmass d frontal-convective events of over 25 mm on Alamogordo Creek are shown in ble 2. The average ratios of 15-min and 30-min depths to 1-hr depths are 0.56 d 0.81, respectively, for the 37 storms (as compared with 0.66 and 0.88 for lnut Gulch). The two events with maximum 1-hr point rainfall are also shown. infall for durations of 5 to 30 min was about average for the June 5, 1960, orm and considerably below average for the August 21, 1966, storm, indicating at intense rainfall may last longer on some occasions than has been experi-ced on Walnut Gulch. Again, not enough data are available to be certain of is or to assign probabilities to events of the magnitude of June 5, 1960, on amogordo Creek.

Table 2.--*Ratio of storm rainfall depth for various durations to 1-hr rainfall for 37 storms of greater than 25 mm for Alamogordo Creek*

	Duration (min)					
	5	10	15	20	30	60
rage	0.25	0.41	0.56	0.68	0.81	1.0
ge	0.13-0.47	0.25-0.67	0.35-0.98	0.45-0.99	0.63-0.99	---
e 5, 1960[1]	0.20	0.39	0.54	0.69	0.84	1.0
ust 21, 1966[2]	0.20	0.34	0.46	0.55	0.68	1.0

[1]Maximum 1-hr point rainfall (103 mm) on Alamogordo Creek (1955-77).

[2]Maximum 1-hr point rainfall (91 mm) for second greatest event on Alamo-do Creek.

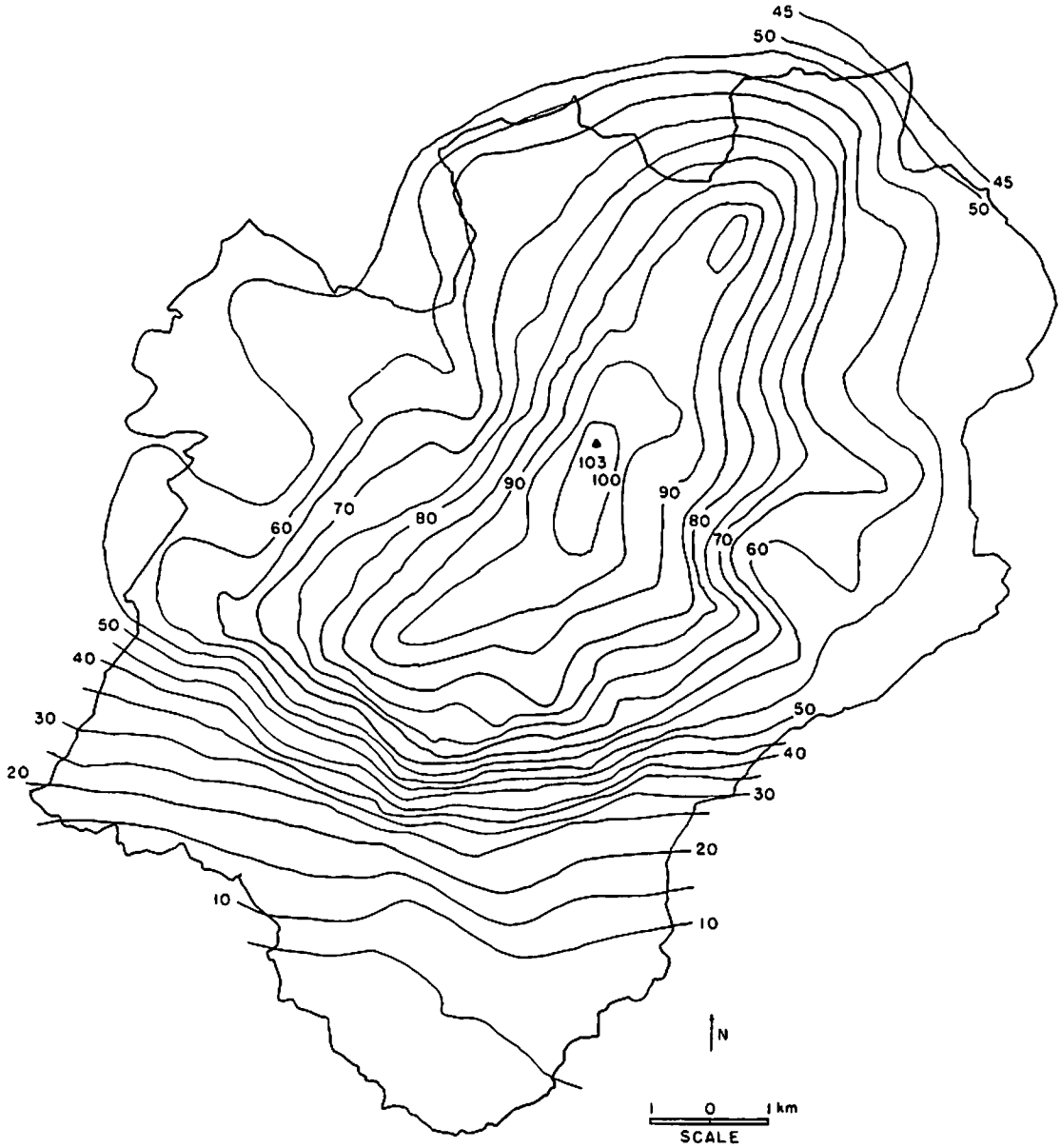


Figure 4.--Maximum 1-hr rainfall, June 5, 1960, Alamogordo Creek. Each contour represents 5 mm of rainfall.

Differences on rainfall volumes for observed maximum 1-hr rainfall are illustrated with rainfall from the maximum events on Walnut Gulch and Alamogordo Creek (tables 3 and 4). The more massive nature of frontal-convective storms on Alamogordo Creek is apparent. For example, the areal extent at the 50-mm isohyets for the Walnut Gulch and Alamogordo Creek storms, respectively, are about 12 and 148 km^2. The total volume of rainfall for the Alamogordo Creek storm was at least three times that of the Walnut Gulch storm, although we could only estimate total areal values.

Table 3.--*Maximum 1-hr rainfall volumes within selected isohyets for storm of September 10, 1967, on Walnut Gulch*

hyet n)	Area (km^2)	Volume (10^6 m^3)	Isohyet (mm)	Area (km^2)	Volume (10^6 m^3)
0	0.2	0.2	35	38.5	18.8
5	.6	.5	30	47.7	21.6
0	1.4	1.1	25	57.0	24.1
5	2.6	1.9	20	[1]66.8	[1]26.3
0	4.1	2.8	15	[1]79.3	[1]28.5
5	6.7	4.3	10	[1]104.0	[1]31.6
0	12.4	7.3	5	[1]124.0	[1]33.1
5	22.8	12.2	0	[1]155.0	[1]33.9
0	31.1	15.8			

[1]Partial storm areas and volumes recorded only within the rain gage work.

Table 4.--*Maximum 1-hr rainfall volumes within selected isohyets for storm of June 5, 1960, on Alamogordo Creek*

hyet m)	Area (km^2)	Volume (10^6 m^3)	Isohyet (mm)	Area (km^2)	Volume (10^6 m^3)
5	2.3	2.2	45	[1]153	[1]101
0	8.0	7.1	40	[1]154	[1]102
5	16.3	14.8	35	[1]155	[1]102
0	25.4	22.2	30	[1]156	[1]102
5	34.2	29.1	25	[1]157	[1]103
0	43.8	36.1	20	[1]159	[1]103
5	66.8	51.8	15	[1]161	[1]103
0	97.6	71.0	10	[1]162	[1]103
5	124	86.0	5	[1]164	[1]104
0	148	98.5	0	[1]174	[1]104

[1]Partial storm areas and volumes recorded only within the rain gage work.

Depth-area curves for maximum 1-hr rainfall for the storms of June 5, 1960, June 16, 1966, and for maximum 6-hr storms for August 21, 1966, on Alamo- do Creek are plotted along with depth-area curves for "record" Walnut Gulch rms (fig. 3). The curves for Alamogordo Creek are much flatter than those Walnut Gulch. Also, the longer durations plot above the shorter durations, icating that, for frontal-convective events, storm areas generally increase h increasing depths.

TIME DISTRIBUTION

Because of the nature of airmass thunderstorms, rainfall time distribution both at a point and over a small watershed (up to 150 km^2) for major events has relatively little effect on flood peaks and volumes (Osborn and Laursen, *1973*). This is primarily true because the intense "core" of runoff-producing rainfall occurs as one unit and is much greater than the light rains that often follow and sometimes precede heavy rainfall. Based on Walnut Gulch data, intensities for major airmass thunderstorms are on the order of 125 mm/hr for about 30 min or a little longer, whereas intensities during the mature and dissipating stages are generally more on the order of 2 to 3 mm/hr. Also, intense rainfall tends to begin and end very abruptly.

As an example, histograms of maximum point rainfall for three of the four largest runoff-producing airmass thunderstorms on Walnut Gulch are shown in figure 5. In all four cases, including the one not shown, over 90 percent of the rain fell in less than 60 min, and intensities outside the core of runoff-producing rainfall were too low to cause runoff. In almost all cases on Walnut Gulch, runoff-producing point rainfall lasted less than 60 min.

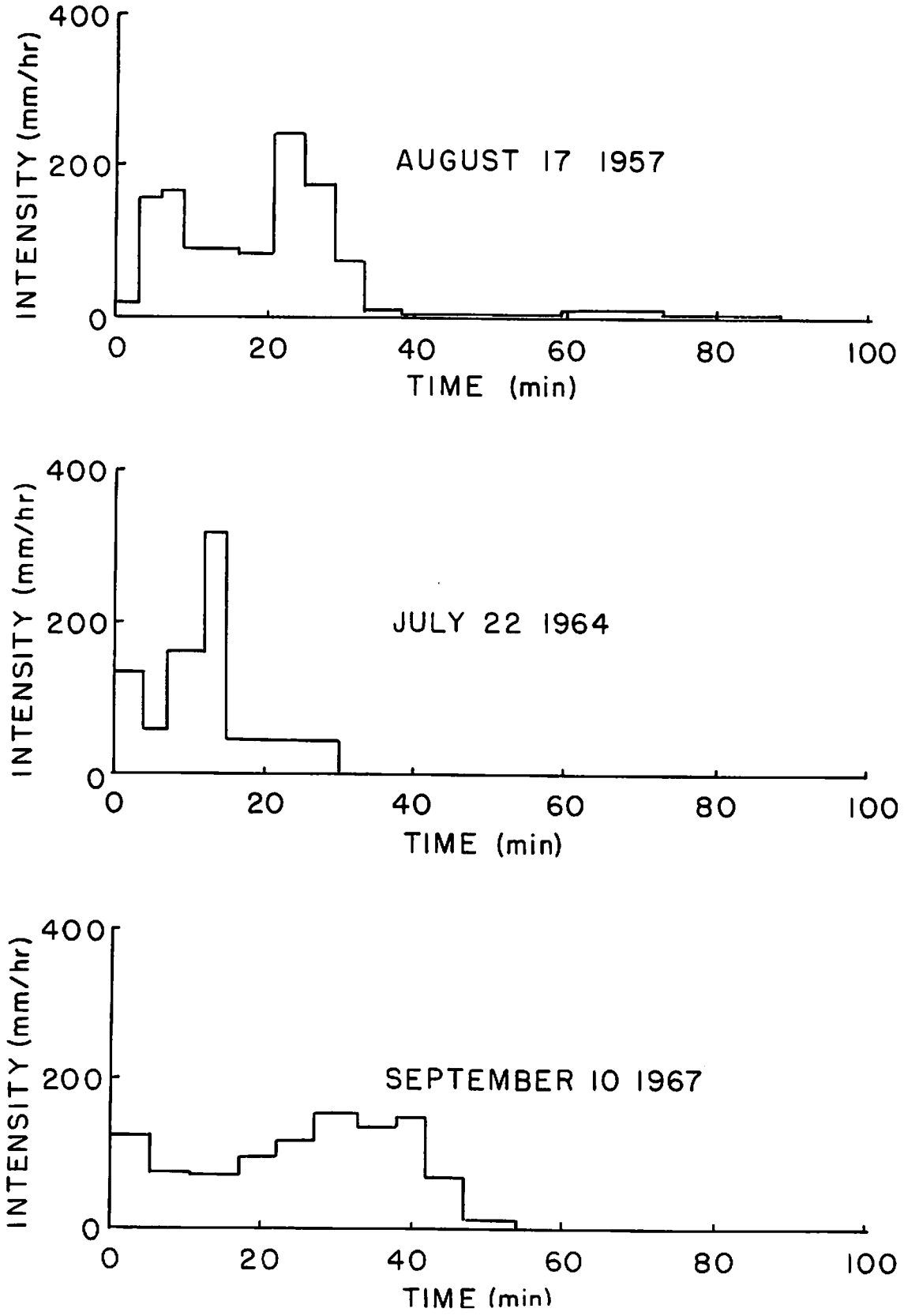
On the other hand, in eastern New Mexico, where frontal activity in combination with convective heating often affects rainfall, the time distribution of rainfall can have a significant effect on flood peaks and volumes. Histograms of three major runoff-producing events are shown in figure 6. Rainfall is concentrated within 60 min during two of the three events. The third event (on August 21, 1966) was distinctive in that intense thunderstorm rainfall was superimposed on a heavy frontal-type rain with heavy runoff resulting.

STORM MOVEMENT

Stream channels in arid and semiarid regions are generally ephemeral and can abstract large volumes of runoff in the normally dry channels. These abstracting channels add to the complexity of thunderstorm rainfall-runoff relationships. From our observations, storm movement appears to have little effect on major flood peaks for small watersheds. If the storm moves up the watershed, runoff moves more rapidly through the wetted channels, whereas if the storm moves down the watershed, the slower moving early runoff tends to arrive at the outlet at the same time as runoff closer to the outlet. In both cases, peak discharges are similar for similar rains; however, storm movement can significantly affect flood peaks and volumes for smaller events. If the storm moves too rapidly, either across, up, or down the watershed, the reduced surface runoff can be all, or mostly, abstracted in the channels above the watershed outlet.

REGIONAL RAINFALL MODEL

The regional rainfall simulation model is based primarily on two existing computer rainfall models. The first is a stochastic depth-area model of airmass



ure 5.--Histograms of three major runoff-producing events on Walnut Gulch.

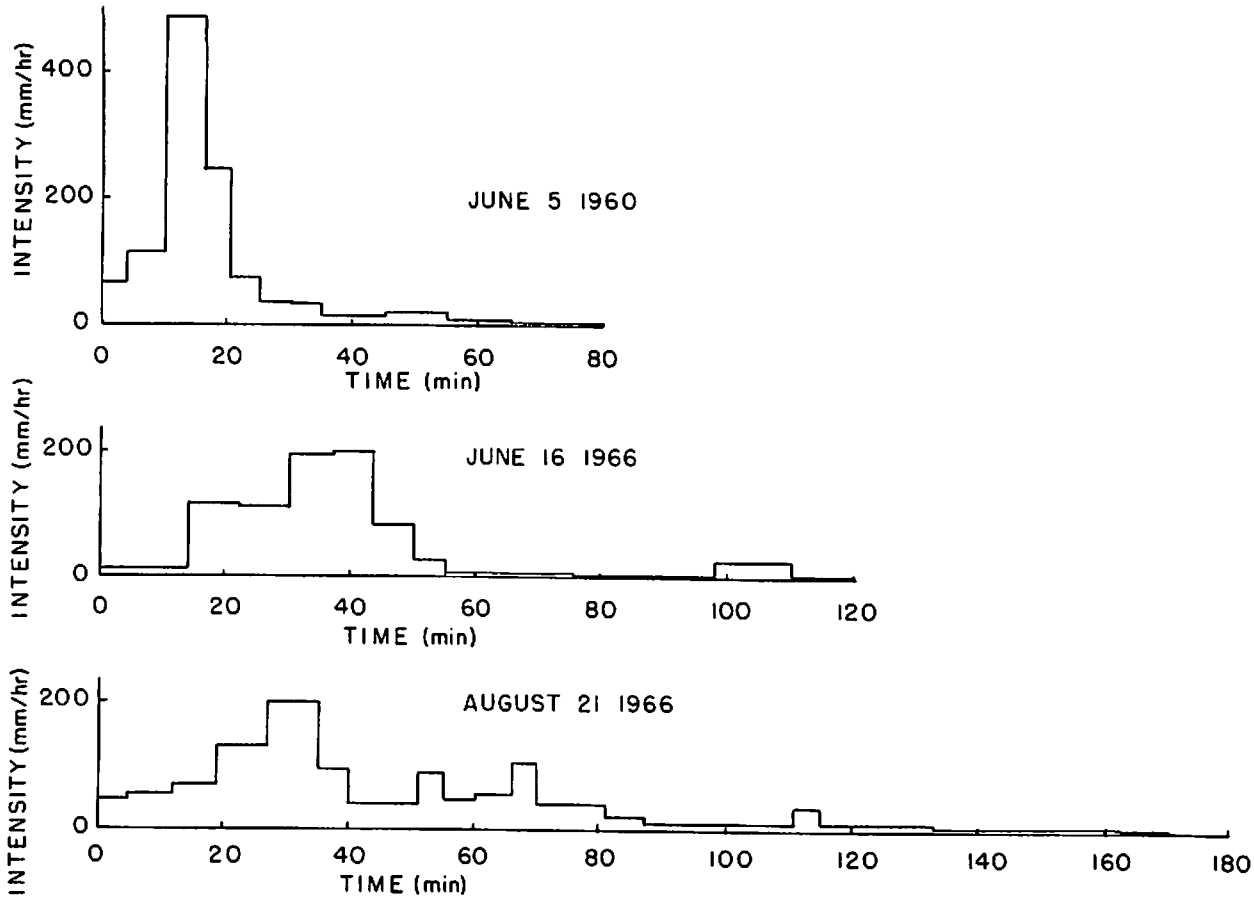


Figure 6.--Histograms of three major runoff-producing events on Alamogordo Creek.

thunderstorm rainfall that was developed with recording rain gage records from the Walnut Gulch Experimental Watershed (Osborn and others, *1972*; Osborn and others, *1974*). The second simulates daily rainfall occurrence in Arizona and New Mexico (Osborn and Davis, *1977*). In addition to revising and adopting these two models, routines were developed to simulate frontal rainfall and to expand the airmass thunderstorm rainfall model to include frontal convective events. The regional model is a set of easily modified subroutines, so changes can be made in the model as more is learned about rainfall in the Southwest.

Input Data

Comparison of NWS rain gage records and topographic features in Arizona and New Mexico suggested the region could be divided into three relatively homogenous

bregions (fig. 1; Osborn and Davis, *1977*). Subregion 1 is eastern New Mexico; bregion 2 is western New Mexico and northeastern Arizona, and subregion 3 is e remainder of Arizona. The program overestimates rainfall occurrences for tersheds below 300 or above 2300 m in elevation; fixed coefficients in the ogram must be adjusted for watersheds outside these elevation limits. The propriate subregion must be entered along with the parameters--latitude, lon- tude, and elevation--representative of the watershed. The relative coordi- tes of each rain gage (or dummy measuring point), along with Thiessen weights ptional) are also entered.

Probabilities for airmass thunderstorm rainfall are based on seasonal prob- ility curves at base stations in the subregions--Roswell (base station of bregion 1), Las Cruces (base station of subregion 2), and Douglas (base ation of subregion 3). The seasonal curves are adjusted automatically when e watershed latitude, longitude, elevation, and subregions are entered.

Thunderstorm rainfall probabilities for SE moisture (explained in the fol- wing section) are based on a 2-km^2 watershed and are adjusted upward for :ger waterseds. For example, there are, on the average, about twice as many nderstorms on the 150-km^2 Walnut Gulch watershed than on a 2-km^2 subwatershed :hin Walnut Gulch.

Rainfall Occurrence

Available recording rainfall records from USDA experimental watersheds and : NWS rain gage network in Arizona and New Mexico were used to develop the lnfall occurrence routine in the regional model (fig. 7; Osborn and Davis, '7). Two types of precipitation-producing systems were identified--frontal l airmass--with airmass divided as to the source of moisture. Moist air from : Gulf of Mexico is called SE moisture; moisture from the Pacific and the .f of California is called SW moisture. Frontal activity is more likely in

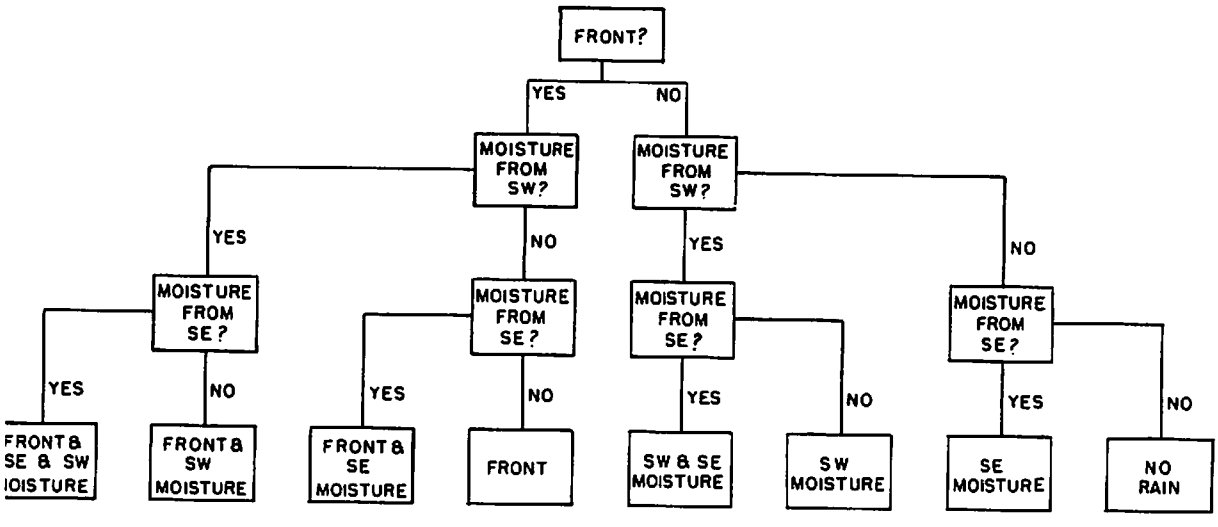


Figure 7.--Simplified schematic of summer rainfall occurrence in Arizona and New Mexico.

:astern New Mexico and northern Arizona than in southern Arizona and southwest-
:rn New Mexico, and has a strong latitudinal component, whereas SE moisture is
ıore common in New Mexico, and SW moisture is more common in Arizona. Both have
strong longitudinal component. Elevation is the third significant parameter
.n the occurrence routine. Daily rainfall occurrences are determined independ-
:ntly for the three systems, and are combined, when necessary, in the depth-area
ainfall simulation (to be explained later).

We determined frontal rainfall occurrence by using uniform seasonal distri-
ıutions based on watershed location and elevation. An element in the frontal
ubroutine increases rainfall probability on the day after it rains. The chance
f rain is reduced to the original fraction after a dry day. The subroutine
djusts for frontal activity that is more common as we move both north and east
n the region.

We determined SW rainfall occurrence by using an annual uniform distribution
ocation and elevation. With satellite pictures now available, we may be able to
dentify significantly different seasonal probabilities in SW rainfall occurrence
nd to incorporate these differences into the program. The likelihood of SW
ainfall occurrence is much greater in Arizona than New Mexico, and the subrou-
ine incorporates this difference. Also, once SW rainfall has occurred, the
hance of rain on the following day increases (Osborn and Davis, *1977*).

The SE rainfall occurrence routine is more complex. SE moisture is sea-
ɔnal, representing the so-called monsoon in the southwest. We chose base
:ations that appeared representative of each of the three subregions. Daily
:obabilities are automatically modified by a multiplier based on the watershed
ɔcation and elevation. In general, SE moisture increases with elevation and
ɜcreases as we move north and west, and the subroutine allows for this. Al-
ıough separate equations were developed in the model to account for persistence
ı frontal activity and moisture from the southwest, no persistence equation was
ıcluded for moisture from the southeast.

Several investigators have used Markov chain models to predict point rain-
ıll occurrence. Smith and Schreiber (*1973*) assumed all events were of the same
ıpulation and fitted daily rainfall occurrences at three stations in southeast-
n Arizona with a segmented first-order Markov chain model. Woolhiser (*1975*)
.s proposed a three-parameter mixed exponential Markov chain model of daily
infall based primarily on data from the Great Plains area. Possibly this
del, or a variation, could be adapted to the southwest as a substitute for the
re cumbersome empirical equations that are presented here.

Moisture, particularly from the southeast, dominates summer rainfall in
utheastern Arizona. Osborn and others (*1972*) modeled storm occurrence as a
asonal Bernoulli random variable based on occurrence of storms of more than 5
on Walnut Gulch. Since there was no statistical difference in the persist-
ce pattern for major events between simulated and actual data, the model did
t include a persistence equation for southeast moisture.

If a thunderstorm day is simulated, more than one event may occur on that
y. Chances for multiple events are based on Walnut Gulch data. Dates and
pes of rainfall occurrences, simultaneous occurrences, and multiple events
ɜ stored for use in the depth-area program routine.

Time Distribution

Thunderstorms have an extremely complex cellular structure in time and :, which is extremely difficult to model without major simplifications. ›rogram simulates a simplified cellular structure as a vehicle to arrive at output, which in turn can be compared directly with real storm data.

If a thunderstorm is indicated, the program first generates a beginning based on a normal distribution centered at 1700 hr. Each thunderstorm has :en 3 and 12 cells with a mean cell distribution of 6. The cells are .plied by a constant (assumed average cell rainfall duration) to determine :nd time for the "runoff-producing" portion of the event (light rain may for some time after a thunderstorm, but this nonrunoff-producing rainfall t included in the model). Individual cells would not necessarily produce f, but are assumed to be in the active part of the thunderstorm event.

If the occurrence routine calls for a second event, the program will t the routine, but only after determining that the second event begins the first event ends. Beginning times are generated until this occurs.

Depth-Area Rainfall Simulation

The simplest output in the program occurs on a day with only frontal rain. al rain is generated for a point and assumed uniform over the entire shed. For larger watersheds, we may add a subroutine to vary rainfall elevation. Frontal storms must last for at least 3 hr and can extend into ›llowing day.

Many of our assumptions for the dimensions and distribution of the inter- ›mponents of thunderstorm rainfall have been determined by trial and error the simulated and real storm outputs are comparable (Osborn and others, . At this time, we assume depth-area rainfall simulations for SE, SW, and occurrences are the same. We assume a constant radius for airmass thun- ›rm cells. In the future, we hope to be able to identify significant dif- :es in SE and SW events and to program these differences.

The program will generate a rectangular area enclosing the rain gages (or points) entered into the program and establish a buffer area around the ıgular watershed (fig. 8). The center of the first cell is randomly lo- somewhere within the buffer (which includes the watershed area). We as- :he second cell is up to a cell diameter from the first cell and has a ı directional component. The third, fourth, fifth, etc., cells have a di- ›nal component based on the direction between the previous two cells. cell center depths are generated independently for each cell. An example : program at this point is shown in figure 9.

›nce the center depths are determined, the rainfall is distributed and ac- ıted at all designated rain gage or dummy measuring points. Average :hed rainfall is determined from the Thiessen weighting, and can be :d out in the final program. Point event totals are printed out and can

be used to plot isohyetal maps (fig. 10).

When frontal and thunderstorm events are simulated on the same day, the program combines the elements of both storm types. First, frontal rainfall is simulated and distributed to each gage. Then, the cells are simulated as described previously. Based on data from the Alamogordo Creek rain gage network, we assume that cell diameters and depths are greater for the frontal-convective simulation.

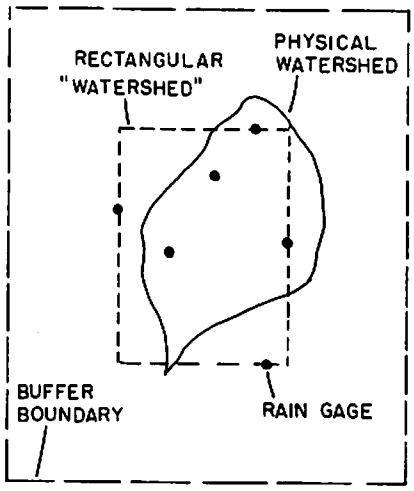


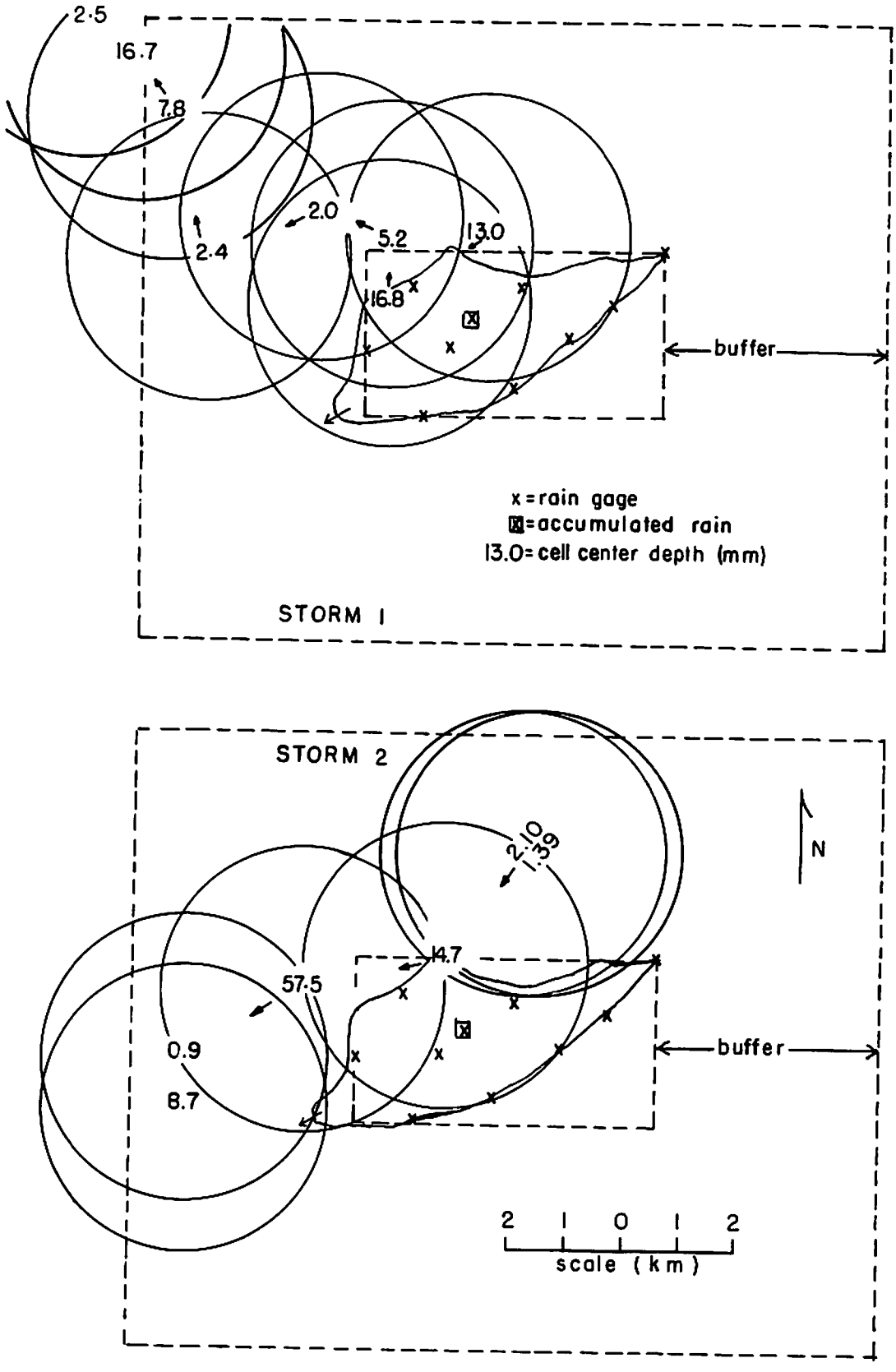
Figure 8.--Rectangular watershed and buffer area created in the depth-area rainfall subroutine.

EXAMPLE OF OUTPUT

The user output can be best described by simulating rainfall in an actual situation. We simulated rainfall on a small (8 km^2) subwatershed (W-11) on the Walnut Gulch Experimental Watershed near Tombstone, Ariz.

There are 10 recording rain gages on or immediately adjacent to W-11. The relative location and Thiessen weight for each gage must be entered into the program (table 5). The program will establish a rectangular watershed and buffer (fig. 8). In practice, most gages are "dummy" locations used to identify the watershed boundaries and to register simulated rainfall at a point. The latitude, longitude, and average watershed elevation also must be entered into the program. The program can be instructed to simulate rainfall for an entire year, or any portion thereof; we have concentrated on the thunderstorm season. A typical season for W-11 is shown in table 6. Rainfall is concentrated in July and August with almost all rainfall occurring from airmass thunderstorms.

Once it has been established that thunderstorm rainfall occurs on a particular day based on a given probability for that day, there is a lesser chance of a second storm occurring, and then a third, and so on. The program will generate a series of rainfall cells starting within the subject watershed or buffer area. In our example, shown in figure 9, the program predicted two



igure 9.--Simulated storm cell development on a Walnut Gulch subwatershed.

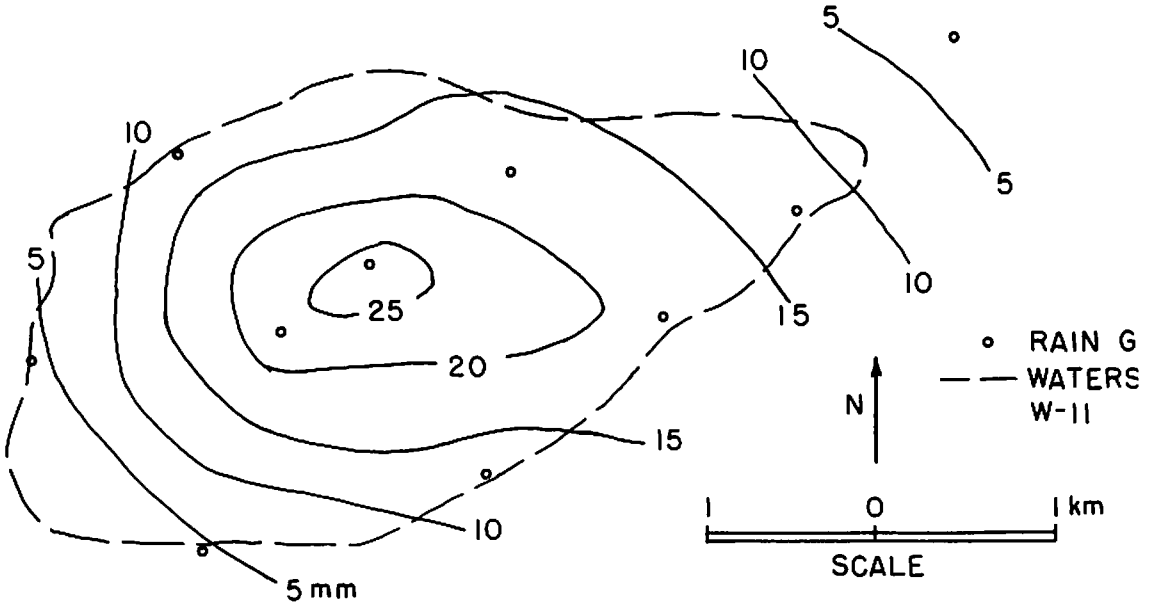


Figure 10.--Isohyetal map of simulated storm rainfall on a Walnut Gulch subwatershed.

Table 5.--*Location of rain gages on or near Walnut Gulch subwatershed h*

Gage No.	Inside (I) or outside (0) watershed	X-ordinate (km)	Y-ordinate (km)	Thi we
51	I	6.48	6.28	0.
89	0	7.34	7.45	.
90	I	7.95	6.45	.
52	I	7.52	5.24	.
54	I	9.26	7.34	.
88	I	8.44	6.83	.
56	I	9.15	5.67	.
94	I	11.79	8.14	.
55	I	10.91	7.17	.
91	0	10.14	6.57	.

thunderstorm events, which lasted from 0900 to 0940 and 2150 to 2220, res tively. In the first event of the day, there were eight cells with cente depths ranging from 1.2 to 10.1 mm. In the second event, there were six with center depths ranging from 0.6 to 34.5 mm.

Accumulated rainfall is printed out for any selected gage(s). The h and low years and 10-yr mean for a centrally located gage are shown in fi

Day	No.[1]	Types	Day	No.[1]	Types	Day	No.[1]	Types	Day	No.[1]	Types	Day	No.[1]	Types	Day	No.[1]	Types
121			149			177			205	1	SE	233	1	SE	261		
122			150			178			206			234			262		
123			151			179			207			235	1	SE	263		
124			152			180			208	1	SE	236	1	SE	264		
125			153			181			209	2	SE	237			265		
126			154	1	SW	182	1	SE	210	1	SE	238			266		
127			155	1	SW	183	1	SW	211			239			267		
128			156	1	SW	184			212			240			268		
129			157			185	1	SW	213	1	SE	241			269		
130			158			186	1	SW	214	1	SE	242			270		
131			159			187	2	SE	215			243			271	2	SW
132			160			188			216			244			272	1	SE
133			161			189	1	SE	217	1	SW	245			273		
134			162			190			218	1	SE, SW	246			274		
135			163			191			219			247			275		
136			164			192			220			248			276		
137			165			193			221	1	SE	249	1	SE, F	277		
138			166			194	2	SE, SW	222	1	SE	250	1	SE	278		
139	1	F	167			195	1	SE, SW	223			251	1	SW	279		
140			168			196			224			252	1	SW	280		
141			169			197	1	SE	225	1	SE	253			281		
142			170			198	1	SE	226			254			282		
143			171			199			227			255			283		
144			172			200			228			256			284		
145	1	SW	173			201	1	SE	229			257	1	SW	285		
146	1	SW	174			202	1	SW	230			258			286		
147	1	SW	175			203	1	SW	231	1	SE	259			287		
148			176			204			232	1	SE	260			288		

[1] Number of thunderstorms on given day.

By chance, early season rainfall for both years was below average. In .s example, the high year resulted from heavy rains in September. Based on yr of record from Walnut Gulch, such heavy September rains occur on the :rage of about once every 5 yr, and analysis of Walnut Gulch rain gage data licates that September rains are not correlated with July-August rainfall. : program can be instructed to print out any or all designated gage accumula- ›ns as well as the areal distribution and watershed average for all events.

The program output can be used for many purposes. For example, isohyetal ›s can be constructed for any event (fig. 10) or for seasonal or annual pre- ›itation. Thiessen weighted averages can be computed. Average or point :ershed rainfall can be used directly as input to hydrologic models to obtain : probability distribution function of peak discharge and storm runoff. The ›sonal rainfall distribution at a centrally located gage (or gages) can be :d as input for range condition models or to estimate the probable outcome of ›ge renovation programs. The latter may be particularly important, since hy- ›logic data are usually lacking when range renovation programs are evaluated. ›o, model output would be used, for example, to estimate the EI (rainfall :rgy) factor in the Universal Soil Loss Equation (USLE) and to predict ero- ›n and sediment yields given other appropriate models.

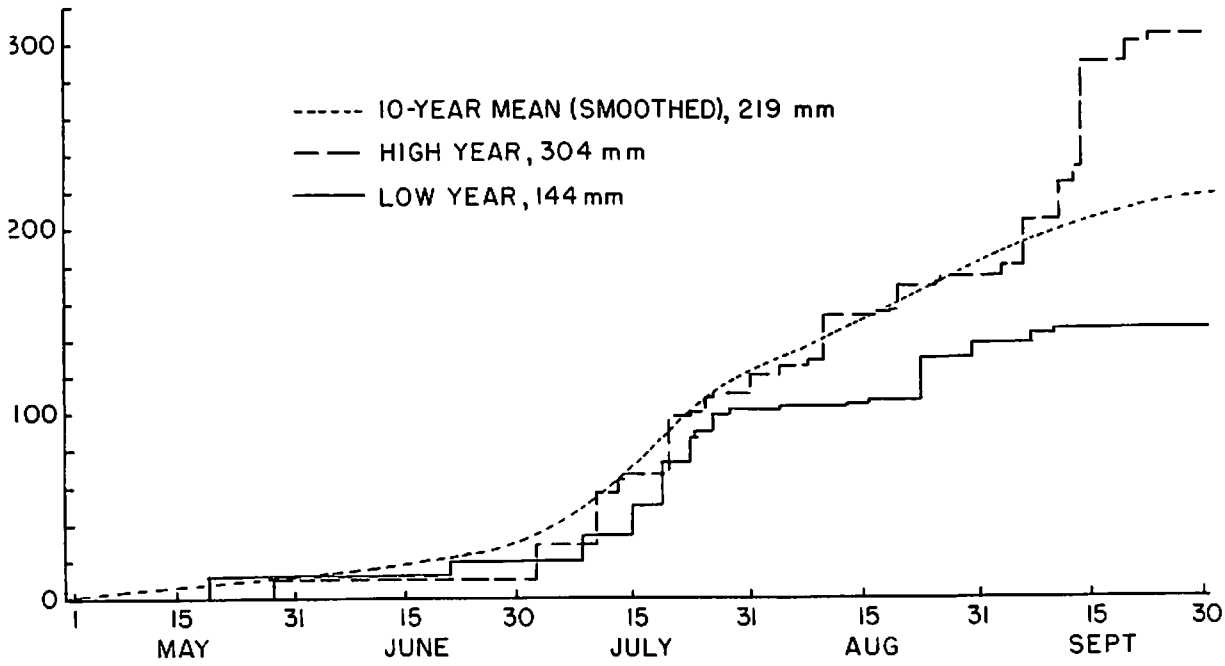


Figure 11.--Smoothed mean and maximum and minnimum accumulated seasonal rainfall for 10 yr of simulated rainfall.

SUMMARY AND CONCLUSIONS

Precipitation in Arizona and New Mexico occurs primarily from frontal ac- ›ity or convective systems or a combination of both. Summer rainfall in the :m of thunderstorms is extremely variable both in time and space, whereas

ntal rainfall is more evenly distributed (Osborn et al., *1979*). Models of h the occurrence and areal extent of rainfall are necessarily simplified.

A model has been developed that simulates rainfall occurrence and amounts ungaged watersheds up to 150 km^2 and elevations between 300 and 2300 m in zona and New Mexico. The model is a combination of many subroutines with a ber of alternative inputs and outputs. The model simulation includes accu- ated seasonal rainfall for any designated rain gage, point totals for indi- lual events, starting and ending times for all events, and Thiessen weighted rages. The model output can be used, for example, to simulate thunderstorm infall, which in turn can be used to predict the distribution and magnitude peak discharges and runoff volumes for ungaged watersheds. The model output also be used to estimate erosion and sediment yield from small watersheds l as input to more complex range renovation or management models.

Many range management or renovation treatments proposed by ranchers rely vily on rainfall as the "make or break" variable of the treatment. These atments could be tested before implementation by simulating rainfall for ying conditions and then determining the corresponding impact on the range agement treatment. This preliminary testing could reduce the risk of atment failure and economic and resource loss.

The program is available by writing to: USDA Southwest Rangeland Water- ed Research Center, 442 East Seventh Street, Tucson, Ariz. 85705.

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APPENDIX

The main program, SATDOR (Space and Time Distribution of Rainfall) (fig 12), is broken down into a number of subroutines (fig. 13). This allows the operator to easily modify specific procedures simply by adding the parts of interest. The function of each subroutine is explained so that the operator will understand its role in SATDOR. To insure consistancy of the sequence, when the program first starts, the day before the start of the season is assumed to have no rain. The program proceeds on a consecutive daily basis.

There are seven major subroutines; three are made up of minor subroutin (fig. 13). The first three are required to generate rainfall occurrence; th next two are used to generate the spatial distribution of rainfall; and the last two are used to determine the temporal distribution of rainfall events. The seven subroutines are:

(1) WSHED - Definition of watershed boundaries and gage locations.

(2) PDF - Probability distributions and parameters for rainfall occurrence defined.

(3) DROM - (Daily Rainfall Occurrence Model) - Generates daily rainfall occurrence record.

(4) SPAR - (Space Parameters) - Spatial parameters defined and calculated.

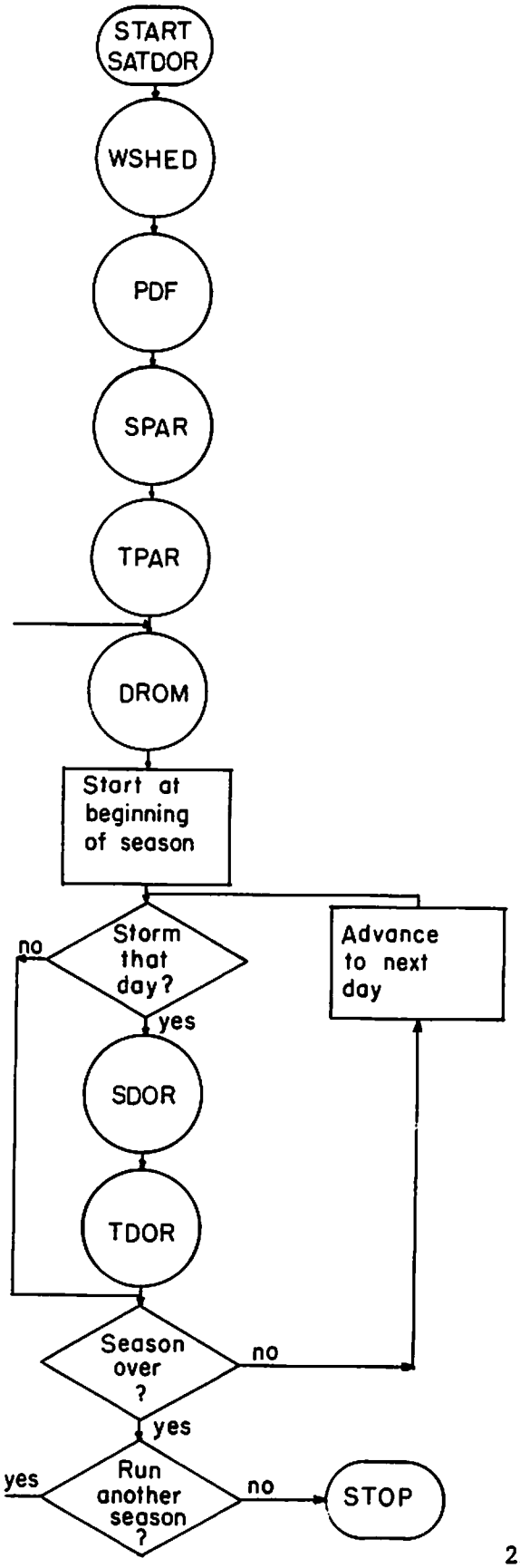

Figure 12.--Flow chart and subroutine locations in SATDOR (Space and Time Distribution of Rainfall).

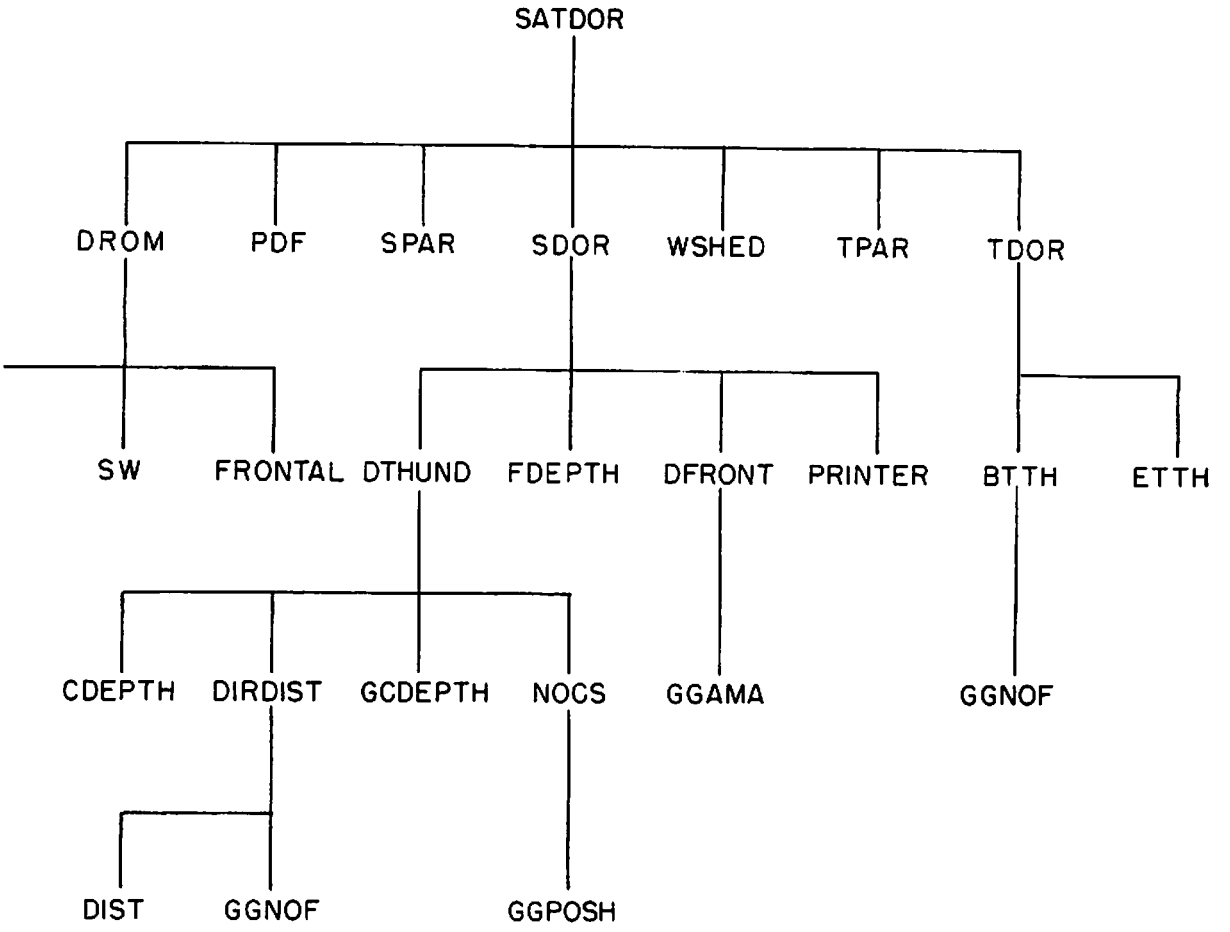

Figure 13.--Subroutine linkage in SATDOR.

(5) SDOR - (Space Distribution of Rainfall) - Spatially distributes rainfall for individual events.

(6) TPAR - (Time Parameters) - Temporal parameters defined and calculated.

(7) TDOR - (Time Distribution of Rainfall) - Distributes rainfall temporally.

:D

The WSHED subroutine reads in the rain gage numbers, whether the gages are the physical watershed, the x and y coordinates of each gage, and the Thiessen ght of each rain gage. Then, the maximum and minimum coordinates are used to ablish a rectangluar rainfall area. Even though the physical watershed is ally some irregular shape, the rain gages will be used to define a rectangle. rectangular area is computed and printed. A buffer of 4 km is added to each e of the rectangle so that simulated storms may form both outside and inside watershed (fig. 8). At present, the buffer is constant, but we are investiing whether it should vary with watershed size.

The areal adjustment factor (AAF) is also defined in this subroutine. The affects the probability distribution (P) read in by PDF (see PDF section). AAF is a multiplication factor that increases rainfall probability (p) with reasing area, but not in direct proportion to areal differences (fig. 14). equals one for watersheds up to 2 km^2, and is varied upward as rain is simu- ed over larger watersheds. The rainfall probability cannot exceed one.

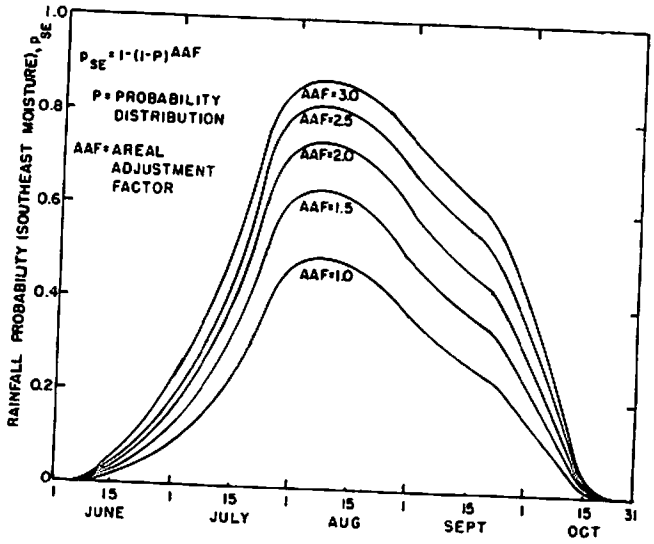

Figure 14.--Method for adjusting SE thunderstorm rainfall probabilities according to watershed area.

The PDF subroutine reads in data used by the DROM subprograms. These data de the watershed location, elevation, region, season beginning, season end an dates), number of seasons to simulate thunderstorms, probabilities of understorms for each region (adjusted by the AAF), persistence of thunder- s from one day to the next, and chances for more than one event on the day.

The DROM subroutine contains three subroutines of its own. These are SE, d FRONTAL (fig. 13), which represent sources of moisture from the princi- urces, the Gulf of Mexico, the Pacific Ocean, and weather fronts, respec- . The SE and SW routines simulate thunderstorms, whereas FRONTAL simu- constant low-intensity rainfall over the specified area. These systems cur in any combination. Watershed location will dictate which combina- are favored. The SE and SW thunderstorms are more massive when combined rontal events.

he SE subroutine determines whether any storms involving this system will based on the thunderstorm probability curve for the watershed region, le, longitude, and elevation. The SE rainfall probability curves at ther than the base site of the region for which the probabilities were

.oped are calculated based on latitude, longitude, and elevation. Also, ;E computations are the only parts of DROM that are affected by the AAF (see above).

The SW and FRONTAL subroutines are very similar. Both have a constant ıbility for rain on a day when there is no rain on the previous day. If : is rain, the following day has an increased chance of rain. The chance ıin after two successive rainy days is decreased and so on. The equations to calculate the daily probability for SW and FRONTAL have different tants; FRONTAL does not include watershed elevation, whereas SW does. Also, ıstant depth is generated when FRONTAL is called, whereas SW calls for lerstorm rainfall.

SPAR reads in spatial parameters (cell diameter, mode distance between ;, number of cells) and calculates shape parameters to be used in the IMSL ɜd routines GGPOSH (a pseudorandom Poisson distributed deviate), GGAMA (a lorandom gamma distributed deviate), and GGNOF (a pseudorandom normally ributed deviate). Parameters and statistics are read in and printed out. : are used in the SDOR subroutine.

The SDOR subroutine is the most complex part of the SATDOR program. There four main subroutines in SDOR with several minor subroutines (fig. 13). :ally, SDOR generates and distributes rainfall to gages on the watershed, ıding upon whether the event is a thunderstorm, frontal storm, or both. is done by using a combination of subprograms particular to a storm type. four main subroutines are:

(1) DTHUND - Generates and distributes thunderstorm rainfall.
(2) DFRONT - Generates frontal rainfall.
(3) FDEPTH - Distributes frontal rainfall.
(4) PRINTER - Prints results of the three previous subroutines.

DTHUND has three subroutines and one function routine of its own; DIRDIST :DEPTH generate location of storm cell centers as well as depths at the centers. DIST is a function of DIRDIST and calculates distance between ; using GGNOF. The SPAR subroutine reads in average cell radius for dif- nt storm types. The distance between cell centers cannot exceed the cell ɜter. The number of cells per storm is generated by NOCS using GGPOSH. If number is less than 3 or greater than 12, NOCS regenerates a number until ; within this range. At present, storm duration is a constant (for each n combination) times the number of cells. GCDEPTH is a function that dis- utes thunderstorm rainfall to each gage according to the distance between gage and the cell centers.

DFRONT uses GGAMA to generate frontal storm depths, and FDEPTH distributes fall evenly to all gages. There is no storm pattern or variation in NT, which may result in significant errors for larger watersheds, but prob- not for small watersheds. The subroutine could be modified to allow for ges in depths with elevation, aspect, and any other topographical influence.

PRINTER prints results of the SDOR subroutines.

AR

TPAR reads in the temporal parameters and calculates shape parameters for e canned subroutine GGNOF and prints out the parameters and statistics. ese values are used in the TDOR subroutine.

DR

Thunderstorm rainfall events are temporally distributed by TDOR using the ictions BTTH and ETTH. The subroutine TDOR also handles the temporal distri- :ion of frontal events. The set of statistics for the starting time, devia- ons, and duration will vary on storm type and if there is more than one storm : day.

BTTH varies with the number of storms per day and with which storm is as- ;ned a beginning time (the second storm must occur after the first is fin- ied). Results are checked to see if they are valid and, if not, regenerated. 'H generates the end time of thunderstorms by indirectly using GGPOSH and the iber of cells.

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