SIMULATION OF RUNOFF-PRODUCING RAINFALL IN THE SOUTHWEST

by

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ABSTRACT

The southwestern United States relies heavily on limited, undependable surface water and limited groundwater resources. Further growth will require reliable estimates of current and potential surface water resources. Procedures are developed for simulating the distribution of runoff-producing rainfall in Arizona and New Mexico, which can be used during design and decision making processes for surface water and land use management.

Existing event-based stochastic models are modified to describe the occurrence, and spatial and temporal distribution of rainfall events. Probability distributions for storm parameters are obtained from analysis of historical data for regional and local areas of investigation. Sequences of rainfall events are simulated using Monte Carlo techniques and potential runoff-producing events are selected to drive a deterministic watershed model. Rainfall configurations are graphically analyzed and simulated runoff from similar and dissimilar storm configurations are analyzed. Rainfall simulation was performed for locations in northeastern and southeastern Arizona and runoff simulation was tested on a wildland watershed in southeastern Arizona.

CHAPTER 1

INTRODUCTION

Economic and associated population growth in the so-called "Sunbelt" is expected to continue steadily into the twenty-first century. Included in the "Sunbelt", is the arid southwestern United States. Water resources will be the most critical limiting factor to further growth in this region.

Growth will primarily occur as increased urbanization industrial development and to a lesser extent, increased agriculture and mining. This region relies on limited, undependable surface water and limited groundwater resources, which are susceptible to overappropriation. Reliable estimates of current and potential water resources must be determined to provide for continued growth.

The objective of this investigation is to provide an improved methodology for estimating rainfall and resulting surface water runoff in the Southwest, in particular, Arizona and New Mexico. Applicaton of the methodology can be used to improve estimates of surface water supplies and the hydrologic impact of current and potential land uses.

The procedures developed can be applied to urban, industrial and wildland environments. In urban settings, information for water supply development, wastewater treatment, drainage design and land use can be improved. In industrial settings, information for wastewater management, drainage design and mitigation of environmental impacts can be improved. The methodology can be especially useful in the mining industry. In wildland settings, water supply, flood control and watershed management can be improved. Some specific uses of the methodology include: reservior and flood retention structure design, storm sewer design, and hydrologic budget analysis and reservior operation.

This investigation was undertaken to develop a method for estimating the recurrence and magnitude of runoff-producing precipitation events in Arizona and New Mexico. The resulting method is a regional precipitation model, capable of simulating the highly variable nature of precipitation events in Arizona and New Mexico.

The regional precipitation model consists of a stochastic occurrence model, and stochastic spatial and temporal distribution models. Simulation by the regional precipitation model generates an annual series of spatially and temporally distributed simulated precipitation events.

Sites selected for calibration and validation are in two different regions in the Southwest: 1) the Betatikin National Monument in northeastern Arizona and 2) the Atterbury Experimental Watershed in southeastern Arizona near Tucson (Figure 1). Watershed response to simulated precipitation events are illustrated for the Upper W-1B subwatershed at the Atterbury Experimental Watershed by simulation of runoff using a deterministic watershed model.

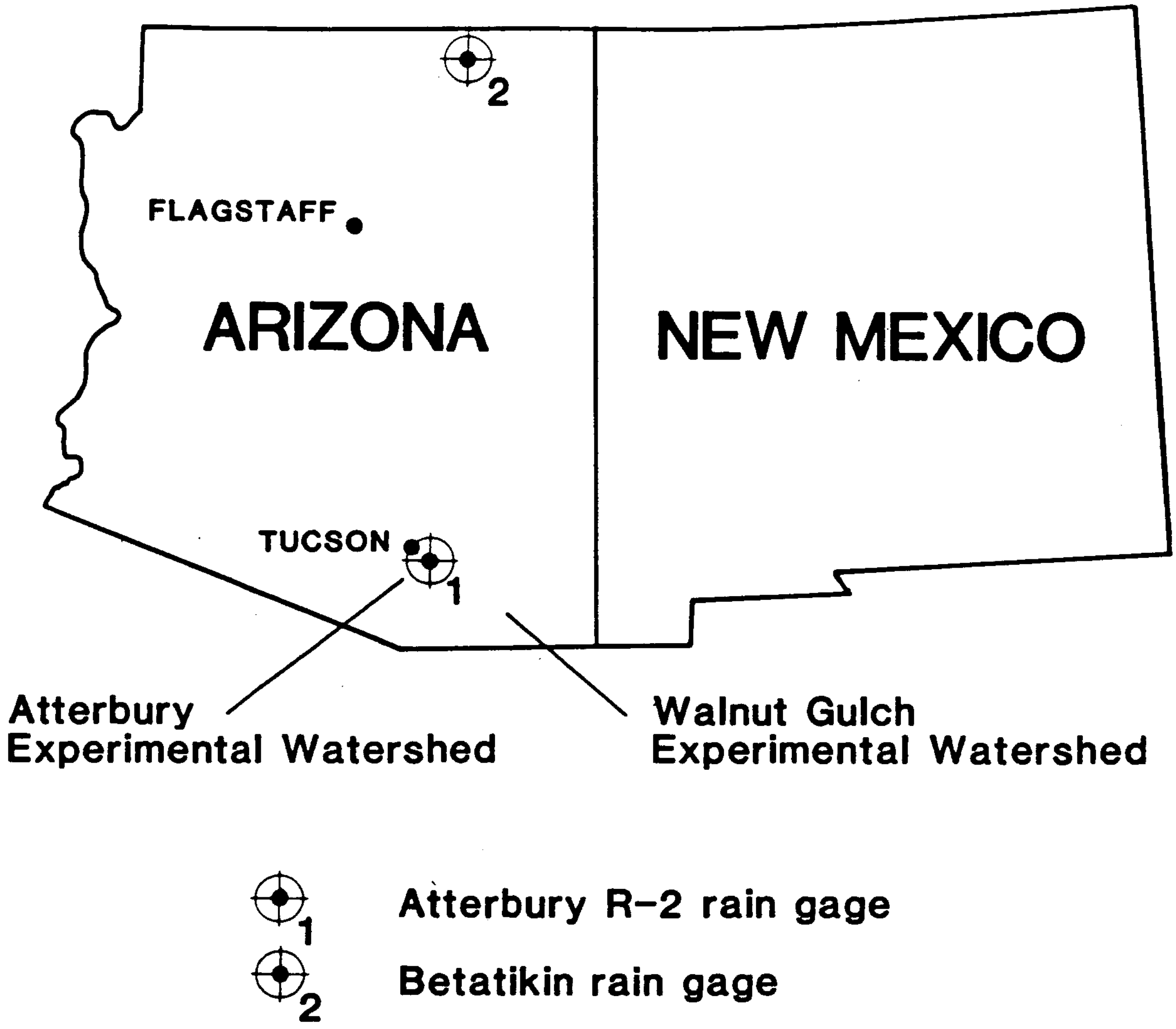


Figure 1. Location map of sites in Arizona and New Mexico used in investigation.

The regional precipitation model was calibrated for two distinctly different regions to show that this model can provide a reasonably accurate estimate of the behavior of precipitation for the entire Arizona and New Mexico region, but with a minimum of effort, can be significantly better when calibrated for site specific use.

CHAPTER 2

LITERATURE REVIEW

Stochastic modeling of precipitation events was first proposed in the early 1940's. It began as an effort to describe the random nature of rainfall which would also serve as a basis to describe the random nature of streamflow.

An early researcher, Le Cam (1961) described rainfall as," a purely random phenomenon subject only to the yearly periodicity. " He also provided the first mathematical descriptions of the areal and temporal behavior of precipitation.

Efforts to model the occurrence and behavior of precipitation in the Southwest are hampered by the highly variable nature of precipitation in the region. Sellers (1960), Osborn and Reynolds (1963), and McDonald (1960) have illustrated and discussed the variability of precipitation in the Southwest as affected by meteorologic and topographic factors. Sellers (1960) suggested that rainfall in Arizona may originate from three storm types. Osborn (1971) suggested that significant precipitation variation exists within the Southwest and may require analysis of regional characterisitics. Osborn and Hickok (1968), and Drissel and Osborn (1968) characterized the seasonal and annual variability of rainfall and rainfall-runoff relationships in the Southwest. About eighty percent of the average annual precipitation falls in the summer months and the subsequent runoff is considerably more variable than the precipitation.

Runoff variability on small watersheds is highly dependent on the spatial and temporal distribution of rainfall on the watershed. Woolhiser and Schwalen (1960) developed the first area-depth-frequency data for thunderstorm rainfall in the Southwest. Fogel and Duckstein (1969), and Osborn and Lane (1972) developed subsequent depth-area relationships to characterize the spatial distribution of rainfall.

Osborn, Lane and Kagan (1971) proposed stochastic models of spatial and temporal distributions of thunderstorm rainfall. Osborn, Mills and Lane (1972) developed a stochastic rainfall occurrence model which could be combined with the spatial and temporal distribution model. Osborn and Davis (1977) improved the above stochastic rainfall occurrence model expanding its applicability from one site to the entire region (Arizona and New Mexico). Duckstein, Fogel and Kisiel (1972) using a different approach also developed a site-specific stochastic model of runoff-producing rainfall for summer type storms.

Improved inputs to watershed or runoff models result from developing stochastic rainfall models, which provide more accurate representations of the physical behavior of rainfall. Osborn and Lane (1969), and Fogel (1969) described the effect of rainfall variability on runoff in semiarid watersheds. Although stochastic models more accurately describe rainfall, Troutman (1983) observed significant error and bias in runoff estimates from a deterministic watershed model using stochastic inputs.

Stochastic rainfall modeling and resulting stochastic runoff modeling deals with complex physical processes and can not be expected to produce "perfect" simulated results. Given simulated results within acceptable error limits, Fogel, Duckstein and Kisiel (1974) and Fogel, Duckstein and Musy (1976) suggest numerous uses of the event-based simulations results in water resources management and design.

CHAPTER 3

METHODOLOGY

The majority of the Southwest has an arid or semiarid climate. Atmospheric sources of moisture in the region generally produce minor amounts of water varying greatly in space and time. The result is a highly undependable surface water resource.

Precipitation in the Southwest, specifically Arizona and New Mexico, varies seasonally. Two distinct seasons occur annually, the winter season and the summer "monsoon" season. The winter season extends from about November 1 to April 30. Precipitation in this period is characterized by low-intensity frontal storms occasionally producing snowfall. The summer season varies significantly with location and generally extends from about May 1 to October 30. Precipitation in this period is characterized by high-intensity convective storms of limited areal extent and some low-intensity frontal storms. The summer season accounts for about seventy to eighty percent of annual precipitation and nearly all surface water runoff. This investigation focuses on the summer season due to the much greater number of significant hydrologic events which occur during this period.

Rainfall in the summer season varies spatially and temporally. The low-intensity frontal events generally occur over large areas. Highly localized events with limited areal extent result from high-intensity convective storms. Low-intensity frontal events are generally of moderate duration, greater than one hour(hr.). High intensity storms are generally short duration events, less than 1 hr. Several high intensity storms can occur on a given day.

A regional stochastic precipitation model, Program SATDOR, was developed to simulate the occurrence, behavior and magnitude of summer season precipitation events. Since summer precipitation occurs as rainfall and most significant precipitation events occur during the summer, the model was developed as a regional stochastic rainfall model concentrating on the summer season. SATDOR generates sequences of daily rainfall which are spatially and temporally distributed. These functions are performed by three major subprograms in SATDOR: 1) DROM (Daily Rainfall Occurrence Model), 2) SDOR (Spatial Distribution of Rainfall), and 3) TDOR (Temporal Distribution of Rainfall).

Daily Rainfall Occurrence Model

DROM was initially developed by Osborn and Davis (1972) as a point rainfall occurrence model for Arizona and New Mexico. Some of the mathematical relationships and parameters in the model were improved during further work by Osborn (1977). The model is based on daily point rainfall occurrence probabilities observed at numerous gaging sites in Arizona and New Mexico. Daily rainfall occurrence is defined as a measurable amount of rainfall (>0.254 centimeters(cm.)) observed within a 24 hr. period.

DROM relates the observed point rainfall occurrence probabilities with the different climatic conditions observed during the summer season. Sellers (1960) suggested that summer rainfall in the Southwest could be divided into two categories, air-mass thunderstorm rainfall and frontal-convective rainfall. Atmospheric conditions responsible for producing rainfall were observed and classified. These conditions were simplified to represent movement of moisture into Arizona and New Mexico from three sources, the southwest (SW), southeast (SE), and north and west (F) (Osborn and Davis, 1972). SW and SE rainfall were classified as thunderstorm rainfall. F rainfall was classified as frontal rainfall. DROM can simulate the occurrence of one or more of the above atmospheric conditions, duplicating to some extent the physical processes producing summer rainfall in Arizona and New Mexico.

The regional nature of the occurrence model requires that only three parameters need be input to produce simulated data: 1) elevation, 2) latitude and 3) longitude. The regression relationships developed for DROM were estimated for English units. This paper was written in metric units. Input data for DROM specifies metric values, however, these values are merely converted to English equivalents rather than recomputing the various regression equations.

Frontal Rainfall Occurrence

The probability of frontal rainfall on any day during the summer season was assumed constant and expressed by the equation:

$$P_F(n) = 0.10+0.005(101-L_o)-0.01(36-L_a) \tag{1}$$

where $P_F(n)$ = probability of frontal rainfall occurrence,

L_o = longitude, in degrees, and

L_a = latitude, in degrees.

After frontal rainfall occurs, it tends to persist. Persistence is highly correlated with elevation and is shown by the following equation:

$$P_F(n+1) = P_F(n) \frac{H}{1000} \tag{2}$$

where $P_F(n)$ = occurrence probability of previous day and

H = elevation, in thousands of feet.

Given frontal rainfall on the previous day, the probability of occurrence of any subsequent frontal rainfall was assumed constant at 0.75.

SW Rainfall Occurrence

The probability of SW rainfall on any day during the summer season was assumed constant and expressed by the equation:

$$P_{SW}(n) = 0.064+0.000008H+0.009(31-L_a)-0.01(115-L_o) \tag{3}$$

where $P_{SW}(n)$ = probability of SW rainfall occurrence,

H = elevation, in thousands of feet,

L_o = longitude, in degrees, and

L_a = latitude, in degrees.

After SW rainfall occurs, it also tends to persist. Persistence is highly correlated with elevation and is shown by the following equation:

$$P_{SW}(n+1) = P_{SW}(n) \frac{H}{1000} \tag{4}$$

where $P_{SW}(n)$ = occurrence probability of previous day and

H = elevation, in thousands of feet.

Given SW rainfall on the previous day, the probability of occurrence of subsequent SW rainfall was assumed to vary by location, from 0.65 - 0.75.

SE Rainfall Occurrence

The relative occurrence of SE rainfall was estimated for gaging stations in Arizona and New Mewico. Three distinct subregions were indicated by analysis of the relative occurrrence data. These subregions were defined as: I) Eastern New Mexico, II) Central and Western New Mexico, and North-central and -eastern Arizona, and III) the remainder of Arizona (Figure 2).

The probability of SE rainfall during the summer season varied from day to day. Occurrences increased with elevation and decreased with latitude in all three regions. To accommodate these variations, the occurrence probabilities were established for a base site in each region, then those probabilities were adjusted to compensate for the

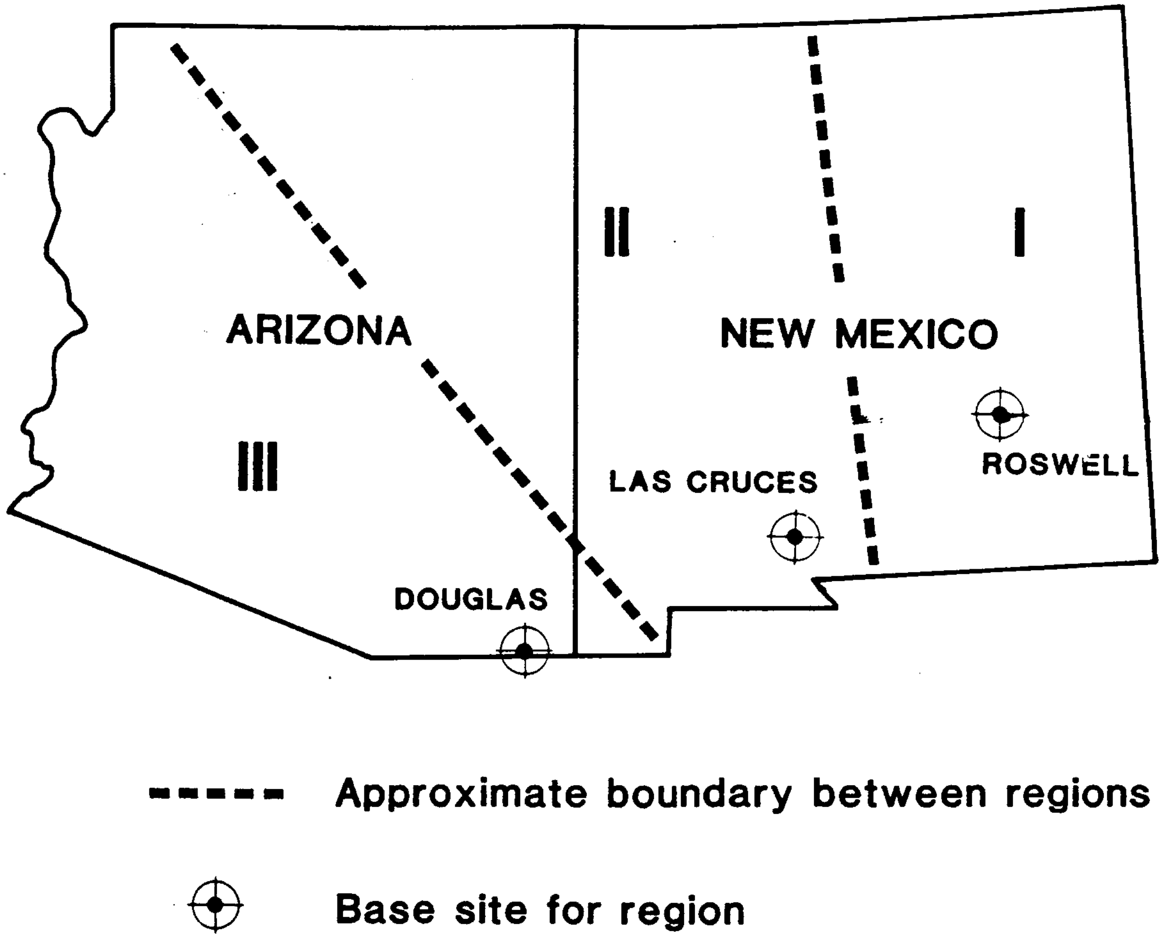


Figure 2. Approximate regions used in developing regression relationships for estimating the occurrence of SE rainfall.

elevation and latitude of the given site. These relationships are presented in the following equations:

$$P_{SE}(n)_{[\text{location}]} = P_{SE}(n)_{[\text{base site}]} \times R \qquad (5)$$

where $P_{SE}(n)_{[\text{location}]}$ = occurrence probability on a given day for a given site,

$P_{SE}(n)_{[\text{base site}]}$ = occurrence probability on a given day at base site, and

R = ratio of probabilities at given and base sites.

The factor R, for a given site, is defined by the following equations:

$$R_{I} = 1.218+0.10(33.4-L_a)-0.11\frac{(3640-H)}{1000} \qquad (6)$$

$$R_{II} = 0.65+0.10(32.4-L_a)-0.02\frac{(3880-H)}{1000} \qquad (7)$$

$$R_{III} = 0.67+0.08(31.5-L_a)-0.09\frac{(4100-H)}{1000} \qquad (8)$$

where R = adjustment factor,

L_a = latitude, in degrees, and

H = elevation, in thousands of feet.

For this model, SE rainfall was assumed to exhibit no persistence. The probability of occurrence of any subsequent SE rainfall is completely independent of rainfall on the previous day.

Combined Rainfall Occurrence

The occurrence probabilities of each rainfall type were determined independently. Consequently, on any given day, an event consisting of any or all of the rainfall types can occur. Simulation of instances of multiple rainfall types represent the occurrence of less frequent, exceptional events.

Multiple Rainfall Occurrences

On a given day, thunderstorm activity has been observed to often produce more than one storm. The occurrence of SW or SE rainfall was assumed to produce from one to three storms. By trial and error, the probability of two or three storms is one-fifth the probability of the previous storm (0.20 or 0.04), respectively (Osborn, et al., 1971).

Point-Area Rainfall Occurrences

DROM was developed and tested for point frequencies of precipitation. Point frequencies were defined as the occurrence of precipitation ($P>0.254$ cm.) on a four square kilometer (km^2.) area (Osborn, 1977). This area was chosen as the area that would minimize the effect of spatially variable rainfall events.

The occurrence model was regionalized to make it applicable to large watersheds. Point frequencies were extrapolated to regional frequencies. For larger watersheds (area>4.0 km^2), point frequencies were adjusted to produce areal rainfall frequencies and correctly simulate the point rainfall at various locations on the watershed. For this investigation, point frequencies were increased by a multiplier, primarily on a trial and error basis, to produce areal frequencies.

For example, on a 4.0 km^2. watershed about 32 occurrences on the area results in 25 events being observed at a point on the watershed. In contrast, on a 28.4 km^2. watershed, about 85 rainfall occurrences on the area would be required to result in about 25 occurrences being observed at a point on the watershed.

Adjustments from point to area rainfall occurrences were calculated in DROM by increasing the basic probabilities for each thunderstorm type as follows:

$$P_{SW\text{-}area}(n) = P_{SW\text{-}point}(n) \times A \tag{9}$$

$$P_{SE\text{-}area}(n)\,[\text{location}] = P_{SE\text{-}point}(n)\,[\text{location}] \times A \tag{10}$$

where P_{SW} = areal occurrence probability for SW rainfall,

P_{SE} = areal occurrence probability for SE rainfall, and

A = areal adjustment factor $(A>1.0)$

Spatial Distribution of Rainfall

SDOR consists primarily of a stochastic thunderstorm cell model initially developed by Osborn, et al., (1971) to describe the behavior of thunderstorms on the Walnut Gulch Experimental Watershed in southeast Arizona (Figure 1). This model was combined with a stochastic model of frontal rainfall and modified, to spatially distribute any rainfall simulated by DROM. Osborn (1971) observed that thunderstorm characteristics such as intensity, depth and duration varied within the Southwest, although storms occurred as a results of similar climatic conditions. Consequently, thunderstorm or frontal rainfall characteristics were assumed to vary from location to location.

Mathematical relationships for SDOR were originally developed in English units. For this paper, the relationships were recomputed to produce metric units.

Frontal Rainfall

The distribution of frontal rainfall was assumed to be uniform over an entire watershed. Frontal storm activity generally encompasses relatively large areas. Since this model is applied to small watersheds (<250 km^2.), the depth of rainfall is assumed constant over the watershed. The depth of rainfall from frontal events was estimated by a gamma distribution as expressed below:

$$f_X(x) = \frac{\lambda(\lambda x)^{k-1}e^{-\lambda x}}{\Gamma(k)} \tag{11}$$

where $x>0$, $\lambda>0$, $k>0$, $\lambda = m_x/\sigma_x^2$, $k = m_x^2/\sigma_x^2$,

m_x = mean depth of frontal rainfall and

σ_x^2 = variance of depth of frontal rainfall (Benjamin and Cornell, 1970).

Thunderstorm Rainfall

The distribution of SE and SW rainfall varies spatially and is estimated by a procedure developed by Osborn, Lane and Kagan (1971). This procedure assumes a multicellular model resulting from the cumulation of randomly grouped unit cells. A unit cell was defined as circular, with the rainfall depth (D) at any point within the cell dependent only on the distance (r) from the center (Figure 3).

Thunderstorm rainfall is spatially distributed by a procedure which creates a random series of circular rain cells moving across a watershed (Figure 3). Rainfall depths within the cells are distributed, then cumulated, resulting in total rainfall received at each point in the watershed. Given a SE or SW rainfall event, steps involved in this procedure are listed below:

1. Simulate the number of unit cells defining thunderstorm.
2. Randomly locate the center of the first cell within the area of investigation.
3. Simulate the direction of movement and distance to the center of all subsequent cells.
4. Generate the depth of rainfall at the center of each cell.
5. Distribute rainfall within each cell and cumulate amounts from each cell to produce total rainfall received for particular event.

The number of unit cells per thunderstorm was assumed to have a Poisson distribution as expressed by the following equation:

$$P_X(x) = \frac{v^x e^{-v}}{x!} \tag{12}$$

where v = mean number of unit cells per storm type (Benjamin and Cornell, 1970).

The stochastic process generates a random variable with a minimum number of three cells and the probability of eight or more cells being

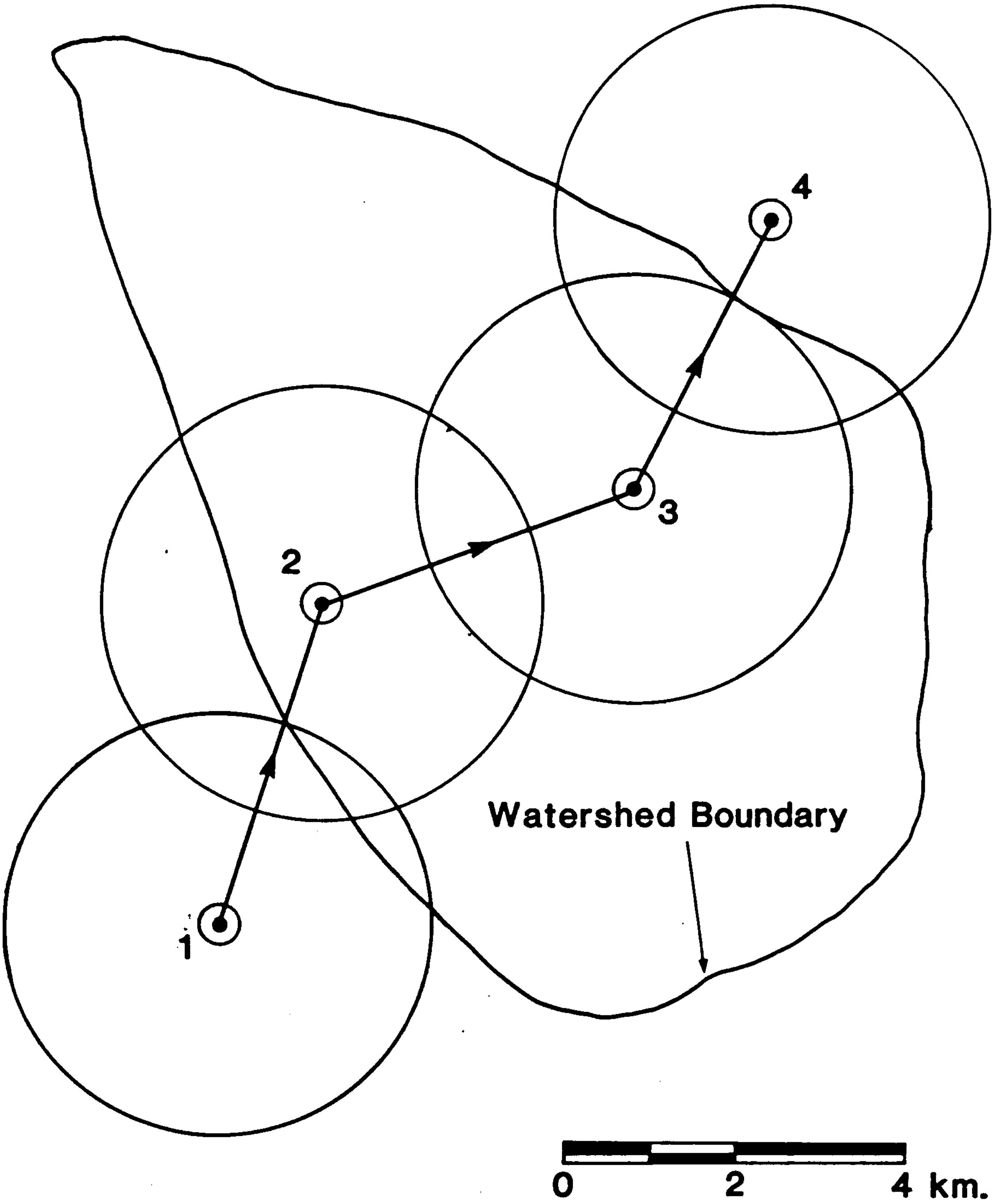


Figure 3. Illustration of unit cell method used for spatial distribution of rainfall.

very small. The number of cells for thunderstorm rainfall and combined rainfall was assumed constant, with the mean number of cells for the combined events being somewhat greater than for the thunderstorm events.

Location of the center of the first cell was simulated by using a uniform random variable to generate coordinates for any point within the defined watershed boundaries. The location of the first storm cell was assumed to be random, but subsequent cells tend to group around the first and follow a general direction of movement. The direction of the second cell from the first can be in any direction. This was generated by a uniform random variable with a range from 0 to 2 pi (6.283185). The direction to subsequent cells has a random component which tends to sustain the direction of storm movement. The random component was generated by a normal distribution with a mean of 0 and standard deviation of +/- one-third pi (1.0471975).

The distance between unit cells centers was estimated from available storm data (Osborn, et al., 1971). Equations listed below were determined to represent these parameters:

$$d = \sqrt{10U} \quad \text{for } U<0.4 \tag{13}$$

$$d = 0.5(10- \sqrt{60-60U}) \quad \text{for } U>0.4 \tag{14}$$

where U = uniform random variable, $0<U<1$, and

d = distance between cells, in kilometers.

Individual cell center depths were approximated by a negative exponential distribution in this form:

$$D_o = \bar{D}_o \ln(1.0-U) \tag{15}$$

where D_o = cell center depth, in centimeters,

$\bar{D}_o$ = mean cell center depth, in centimeters, and

U = uniform random variable, $0<U<1$.

Rainfall records at Walnut Gulch Experimental Watershed (Figure 1) were the basis for the relationship, and with trial and error simulations, the basis for estimating the mean cell depth.

Analysis of rainfall data from Walnut Gulch suggests an approximate relationship between depth of rainfall and distance from the center of unit cell. The following equations represent this relationship:

$$D = 0.9D_o(1.0-K\ln\sqrt{.6214r}) \tag{16}$$

for $r>0.9079328$ km.

$$D = D_o(1.0-\sqrt{0.6214r}) \tag{17}$$

for $r<0.9079328$ km.

where D = depth of rainfall at any point within cell, in centimeters,

D_o = center depth of unit cell, in centimeters,

r = distance from point to center of unit cell, in kilometers,

$K = 1/\ln(\sqrt{\pi}R)$

R = unit cell radius, in kilometers.

Temporal Distribution of Rainfall

TDOR consists of a stochastic model which simulates the starting time and duration for the various rainfall occurrences generated by DROM. For this investigation, beginning times and durations of rainfall were assumed uniform over the entire watershed, For small watersheds (<250 km^2.), this assumption should not have a significant effect on watershed response to rainfall events.

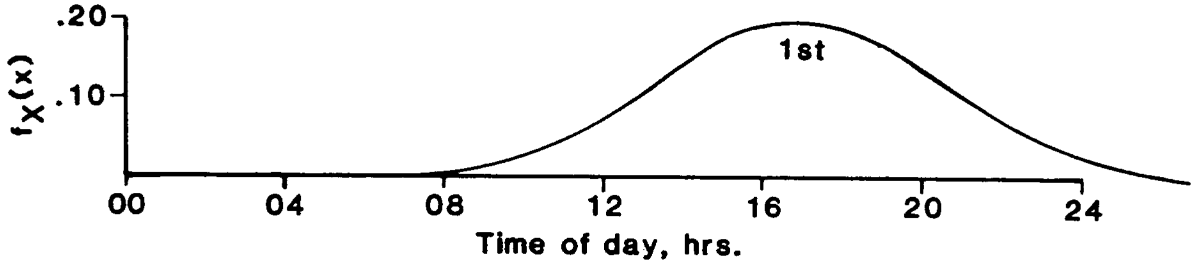
Frontal Rainfall

Low-intensity frontal rainfall can begin at any time during the day and generally lasts for relatively long, intermittent periods (Figure 4). The beginning time for frontal rainfall was simulated by a uniform random variable from 0.00 - 24.00 hours. The duration of frontal rainfall was also simulated by a uniform random variable, resulting in a value, greater than three hours.

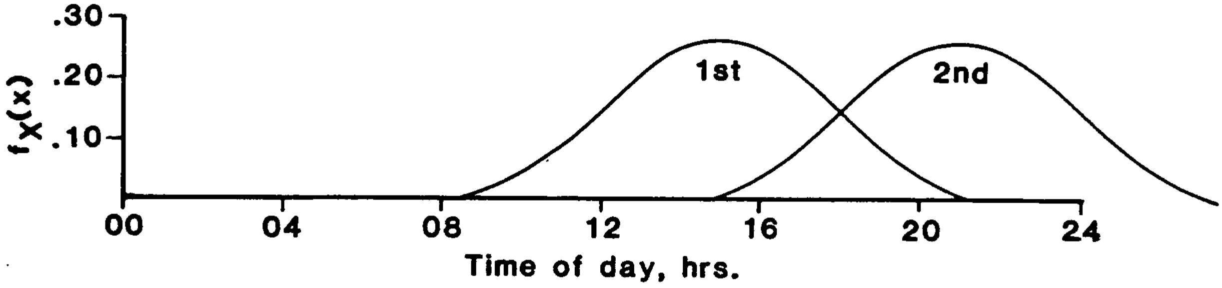
Thunderstorm Rainfall

High-intensity thunderstorm rainfall tends to begin in the late afternoon and generally lasts for relatively short periods (Figure 4). The beginning time for thunderstorm rainfall was simulated by a normal distribution as follows:

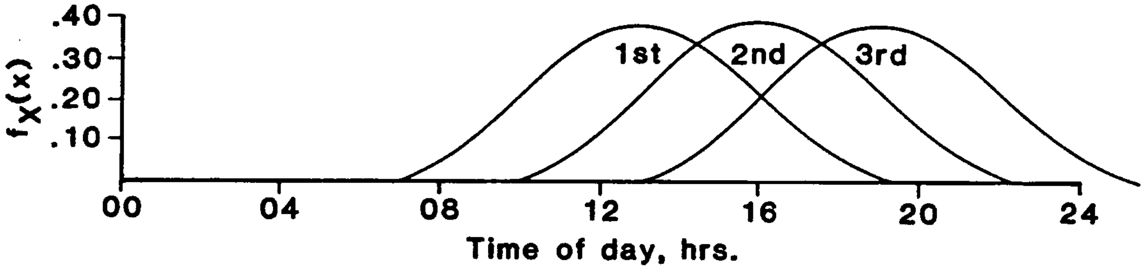
$$f_x(x) = \frac{1}{\sigma_x \sqrt{2\pi}} \exp\left[-0.5 \left(\frac{x - m_x}{\sigma_x}\right)^2\right] \qquad (18)$$



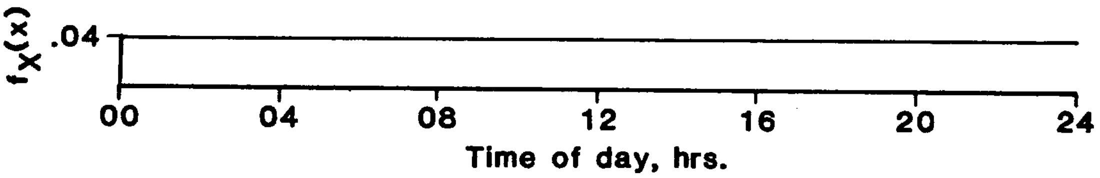
One Thunderstorm



Two Thunderstorms



Three Thunderstorms



Frontal Storm

Figure 4. Probability distributions of beginning times for thunderstorm and frontal rainfall.

where m_x = mean beginning time for thunderstorms and

σ_x = variance of beginning time for thunderstorms (Benjamin and Cornell, 1970).

Mean beginning times varying according to the number of thunderstorms occurring on a given day.

The duration of thunderstorm events were simulated by a gamma distribution previously expressed by equation (11). The duration parameters vary according to storm type, with the duration of combined events being greater than that for thunderstorm events. Duration of storms was assumed independent of the number of thunderstorms on a given day.

Model Operation

SATDOR is a structured FORTRAN program with major functions such as DROM, SDOR AND TDOR performed by major subroutines, and special calculations performed by subroutines or function subroutines. Stochastic variables are generated with pseudo-random numbers supplied by either FORTRAN library function RANF or IMSL library subroutines (IMSL, 1980). Several random variables are generated within SATDOR using RANF results. The remaining random variables are calculated by IMSL library subroutines, GGAMR, GGPOS and GGNQF, which produce pseudo-random deviates of normal, Poisson and gamma distributions, respectively. A program listing of SATDOR is presented in Appendix A and a listing of variable definitions is in Appendix B.

Program SATDOR, the rainfall model, uses one input data file specifying the location data, occurrence probability parameters, and spatial and temporal distribution parameters. Output from SATDOR occurs at various points in the program and can be presented in numerous configurations including rainfall occurrences, spatial distribution and beginning and end times of events, and compiled daily rainfall records.

The operating sequence of SATDOR is listed below. A flow chart of the sequence is shown in Figure 5.

1. Read input data (location data and grid network for watershed, occurrence parameters, and spatial and temporal distribution parameters).

2. Simulate one season of rainfall occurrences (day, storm type, and number of thunderstorms per day, if applicable).

3. Simulate daily spatial distribution of rainfall occurrences (storm rainfall depths at gage locations over watershed).

4. Write storm and spatial distribution data to output and to data file to be used later as input to watershed model for runoff simulation.

5. Simulate daily temporal distribution of rainfall occurrences (beginning time and duration of each storm).

6. Write temporal distribution data to output, and to data file to be used later as input to watershed model for runoff simulation.

7. At completion of simulation of one year of spatial and

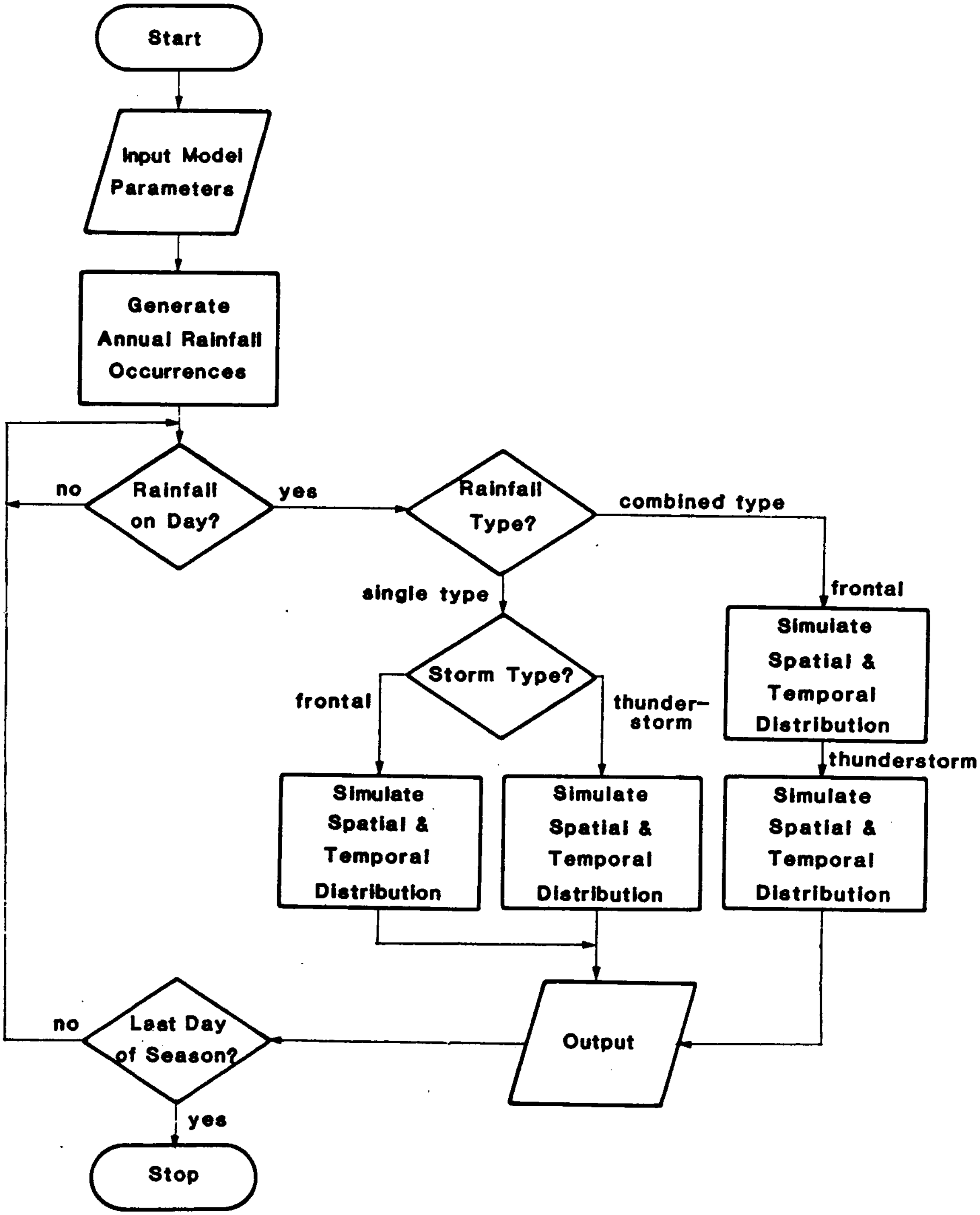


Figure 5. Flow chart for rainfall simulation model, SATDOR.

temporal distribution data, annual daily occurrence (day and storm type) and rainfall amounts (day and amount) are written to data files for statistical analysis of occurrences and rainfall amounts and comparison with existing data, if available.

8. Return to step 2, unless specified number of simulated years completed, in which case, write to output, simulated annual rainfall records, then stop.

A user's guide for SATDOR is presented in Appendix C. It provides a list and explanation of input variables and an explanation of the various output configurations available in SATDOR.

Runoff Simulation

The main purpose of this investigation was to develop methodology that simulated the highly variable nature of summer rainfall in the Southwest. One means of evaluating the effectiveness and accuracy of the rainfall model would be to observe watershed response to simulated rainfall events. Watershed response can be best illustrated as simulated runoff events produced by a watershed model.

For this investigation, program HYMO, a watershed model based on Soil Conservation Service (SCS) rainfall-runoff relationships was chosen to demonstrate watershed response to variability of rainfall produced by SATDOR. HYMO was developed by Williams and Hann (1973) to compute runoff hydrographs, perform flood routing, and estimate sediment yields. HYMO requires limited watershed data (watershed dimensions and soil-vegetation parameters) and provides reasonable estimates of runoff from small watersheds.

Runoff simulation was simplified by lumping all subwatersheds of the Upper W-1B watershed, W-1BX, W-2 and W-3, together. This eliminated the need for separate runoff simulation for each subwatershed and routing of subsequent runoff. Simulated runoff hydrographs represent estimated flows at the outlet of the Upper W-1B watershed.

CHAPTER 4

RESULTS AND DISCUSSION

One hundred year rainfall records were simulated by SATDOR for calibration and adjustment of parameters for the model, then long-term (500 years) rainfall records were simulated for validation with existing daily rainfall records at Atterbury and Betatikin. Validation of occurrence and magnitude of rainfall events involved comparison of simulated point (<4.0 km^2.) rainfall records with existing daily rainfall records.

Spatial and temporal distributions of rainfall events were simulated by SATDOR for calibration and adjustment of parameters for the model, then a long-term series of rainfall events were simulated for subjective validation of rainfall events and analysis of watershed response to simulated rainfall on Upper W-1B subwatershed of Atterbury Experimental Watershed. Validation of spatial distribution of rainfall events involved subjective comparison of isohyetal patterns of significant rainfall events (>1.5 cm.) on Upper W-1B subwatershed with isohyetal patterns observed for actual rainfall events of similar magnitude. Validation of watershed response involved comparison of runoff behavior as simulated by HYMO for several significant rainfall events.

Area of Investigation

SATDOR was developed to simulate rainfall data for the entire Arizona-New Mexico region. Daily rainfall records at Atterbury and Betatikin were chosen for calibration and validation of the model (Figure 1). National Park Service personnel have operated a twenty four hour standard rain gage at Betatikin since 1951, providing 31 years of data. The University of Arizona Water Resources Research Center has operated a recording rain gage at location R-2 at Atterbury since 1955, providing 27 years of data.

Simulated rainfall from the model was applied to Upper W-1B watershed of Atterbury Experimental Watershed to illustrate the effects of rainfall variability on runoff. The Upper W-1B subwatershed (Figure 6) consists of subwatersheds W-1BX, W-2 and W-3, covering 28.4 km^2. and is oblong in shape with a major channel length of 15.5 km. The elevation at the top and outlet of the watershed are 981.4 and 830.8 meters (m.), respectively, producing a change in elevation of 150.6 m. Vegetative cover is sparse consisting primarily of creosote bush (Larrea tridentata), palo verde (Cericidium microphyllum), mesquite (Prosopis juliflora), and ocotillo (Fouquieria splendans) (Hekman and Berkas, 1981). Soils range from sandy to gravelly on the ridges to loams on nearly flat water courses (Hekman and Berkas, 1981).

Simulation of Rainfall Occurrences and Magnitudes

Parameters required by SATDOR to simulate rainfall events were estimated from existing data and by trial and error simulations. Some

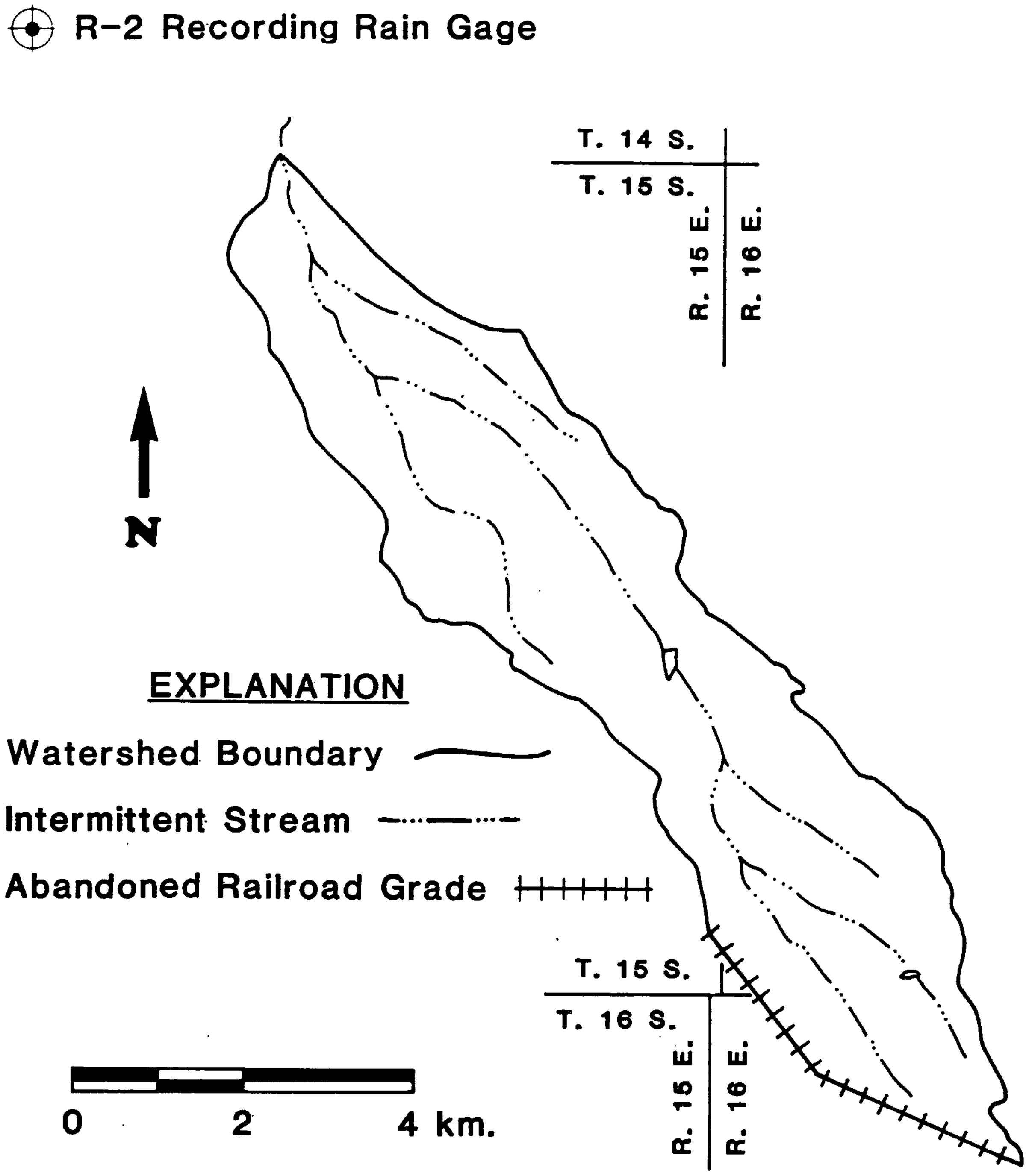


Figure 6. Upper W-1B watershed of Atterbury Experimental Watershed.

of the physical processes modeled by SATDOR were easily theorized and tested. Other processes were hypothesized and appeared reasonable. Data needed to estimate parameters and/or provide testing, in some cases, did not exist or could not be readily obtained.

Simulation of rainfall occurrences and magnitudes for Atterbury and Betatikin were performed using general and site-specific parameters. Parameters for simulation of rainfall occurrences are shown in Table 1. A parameter was introduced into the model to increase or decrease the probability of rainfall occurrences for application and testing at specific locations and is referred to as the Probability Adjustment Factor (PRAF). Parameters for simulation of spatial distribution of rainfall are shown in Table 2.

DROM was designed to generate the average number of events per season and an approriate proportion of different storm types for the particular region. The proportions of storm types established by Osborn and Davis (1977) were assumed to still apply although ten more years of rainfall data is now available. The average number of events per season, based on a regression analysis with latitude, longitude and elevation as independent variables, could easily change with the addition of this data.

For the fifteen year period of data (1958-1972), used to formulate the model, the average number of events per year at Atterbury and Betatikin were 21.93 and 32.27, respectively. The average number of events per year for the complete period of record at Atterbury

Table 1. Parameters used by SATDOR to simulate the occurrence of daily rainfall events at Atterbury and Betatikin.

	Atterbury	Betatikin
Location:		
Region	3	2
Latitude (degrees)	32.18	36.68
Longitude (degrees)	110.84	110.53
Elevation (m.)	829.0	2220.7
Area of Watershed (km^2.)	4.0	4.0
Occurrence Model:		
Persistence of SW	0.75	0.65
Persistence of Frontal	0.75	0.75
Probability of two events	0.20	0.20
Probability of three events	0.04	0.04
Probability Adjustment Factor	0.84	0.93
Areal Adjustment Factor	1.00	1.00

Table 2. Parameters used by SATDOR to simulate magnitude and spatial distribution of daily rainfall events at Atterbury and Betatikin.

	Atterbury	Betatikin
SE Rainfall		
mean no. of cells	4.5	4.5
mean center depth of unit cell (cm.)	1.00	0.90
unit cell radius (km.)	2.50	2.50
SW Rainfall		
mean no. of cells	4.5	4.5
mean center depth of unit cell (cm.)	1.00	0.90
unit cell radius (km.)	4.5	4.5
Frontal Rainfall		
mean depth (cm.)	0.30	0.30
variance of depth (cm.)	0.09	0.09
Combined Rainfall (SE or SW)		
mean no. of cells	5.5	5.5
mean center depth of unit cell (cm.)	1.50	1.40
unit cell radius (km.)	3.0	3.0
mean depth (cm.)	0.30	0.30
variance of depth (cm.)	0.09	0.09

(1956-1982) and Betatikin (1952-1982) were 22.93 and 29.90, respectively. In either case, the average number of events per year for the actual data, were less than the expected number of events to be simulated at Atterbury and Betatikin, 27.27 and 34.79, respectively. DROM was developed to produce expected numbers of seasonal events based on the relationships expressed below:

$$\text{Region 2: } E(N) = 196+0.00398H+0.811L_a-1.99L_o v \tag{19}$$

$$\text{Region 3: } E(N) = 333+0.00467H-3.11L_a-1.97L_o \tag{20}$$

where $E(N)$ = Expected seasonal number of events,

H = elevation, in thousands of feet,

L_a = latitude, in degrees, and

L_o = longitude, in degrees (Osborn and Davis, 1977).

These minor discrepencies indicate the average number of events per year at Atterbury range from eighty to eighty-four percent of the expected number, and at Betatikin range from eighty six to ninety three percent of the expected number. The parameter, PRAF, was assigned values within these ranges for simulation and tested by trial and error to obtain the best value for each site.

Goodness of Fit

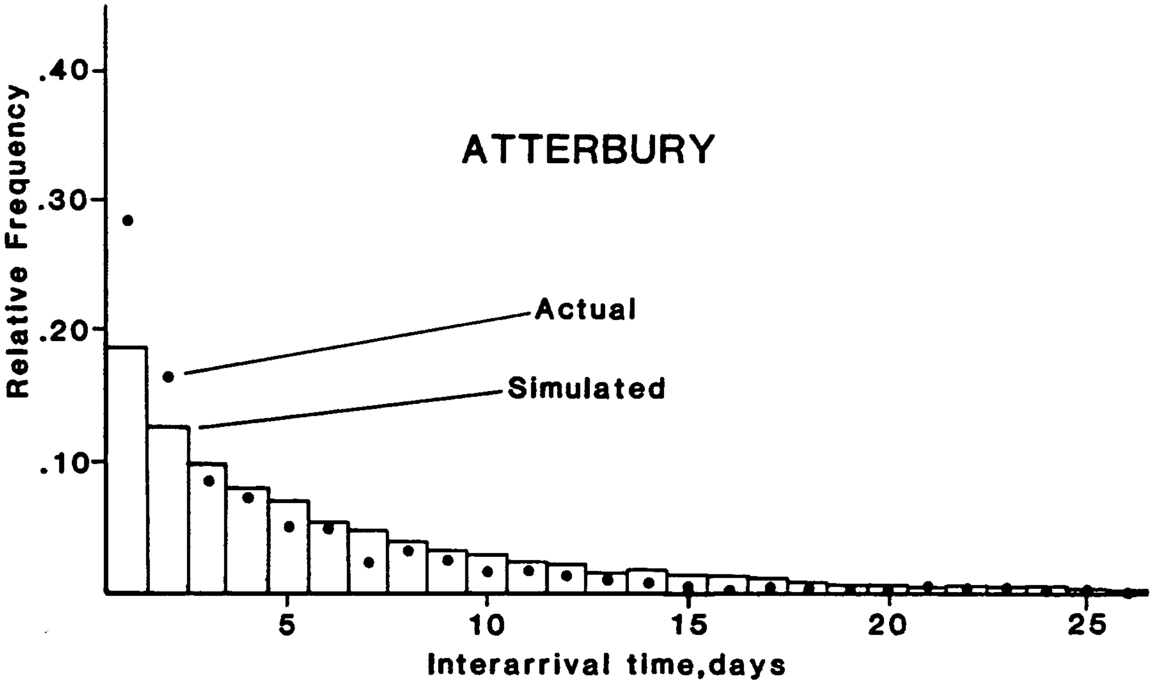
Long-term simulations were performed by SATDOR to test the goodness of fit of simulated rainfall records with actual rainfall records at points, Atterbury and Betatikin. The watershed area for the simulations was set at 4.0 km^2., to make it nearly equivalent to a point. The parameters examined in testing for goodness of fit were mean number of events per season, mean seasonal rainfall, mean interarrival time between daily rainfall events and its probability density function (PDF) and mean rainfall amount per day and its probability density function (PDF). Five hundred years of rainfall records were simulated for Atterbury and Betatikin for the summer season. A comparison of statistics describing the actual and simulated data are shown in Table 3. A comparison of actual and simulated probability density functions for interarrival time and daily rainfall are shown in Figures 7 and 8, respectively.

Analysis of results indicated the simulated data were in reasonably close agreement with the actual data. Mean number of events and seasonal rainfall, interarrival, time and rainfall per day were in agreement with statistics for actual data. The variance of simulated data was slightly less than for actual data. Generally, simulated data is not as widely dispersed as actual data.

Actual and simulated PDF's of Betatikin results were in very close agreement except the lower segments of interarrival times (Figure 7) and daily rainfall amounts (Figure 8). The goodness of fit between actual and simulated distributions for interarrival times and daily rainfall amounts were rejected at a significance level of 0.01 using the Kolmogorov-Smirnov test (Lindgren, 1976). However, goodness of fit for daily rainfall amounts greater than 0.4 cm. could not be rejected

Table 3. Comparison of statistics of actual and simulated rainfall records at Atterbury and Betatikin.

Statistical Parameters	Atterbury		Betatikin	
	Actual	Simulated	Actual	Simulated
Mean no. of rainfall events per season	22.9	22.6	29.9	29.3
Range of no. of rainfall events per season	12-35	10-37	21-51	14-48
Mean seasonal rainfall (cm.)	15.65	15.42	15.87	15.82
Minimum seasonal rainfall (cm.)	6.32	2.54	3.91	6.09
Maximum seasonal rainfall (cm.)	29.92	38.56	33.40	32.43
Interarrival time between events (days):				
mean	7.34	7.50	5.78	5.99
variance	139.98	68.43	65.24	45.72
Rainfall amount per event (cm.):				
mean	0.68	0.68	0.53	0.54
variance	0.66	0.66	0.47	0.45



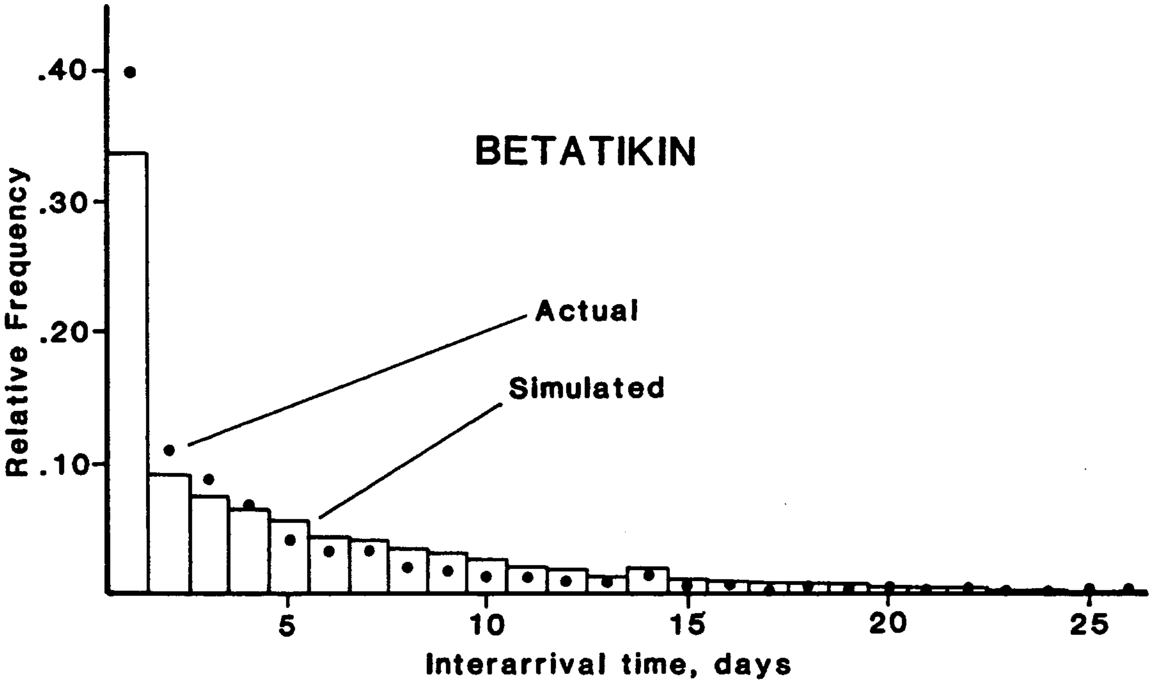
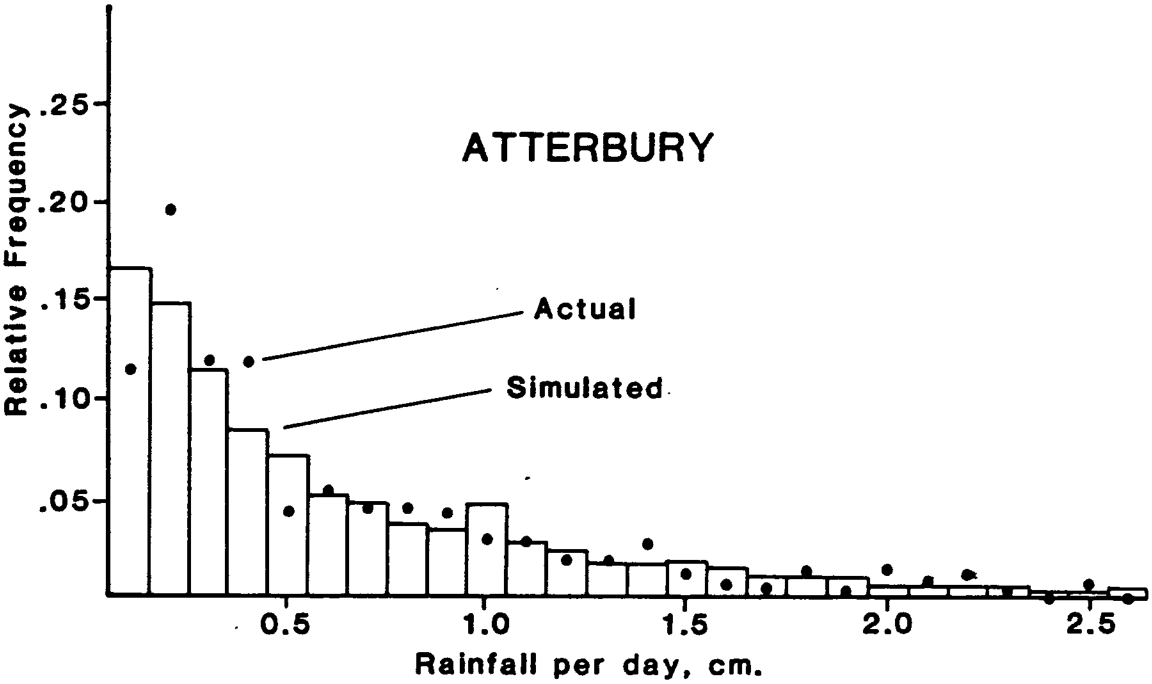


Figure 7. Comparison of actual and simulated probability density functions for interarrival time at Atterbury and Betatikin.



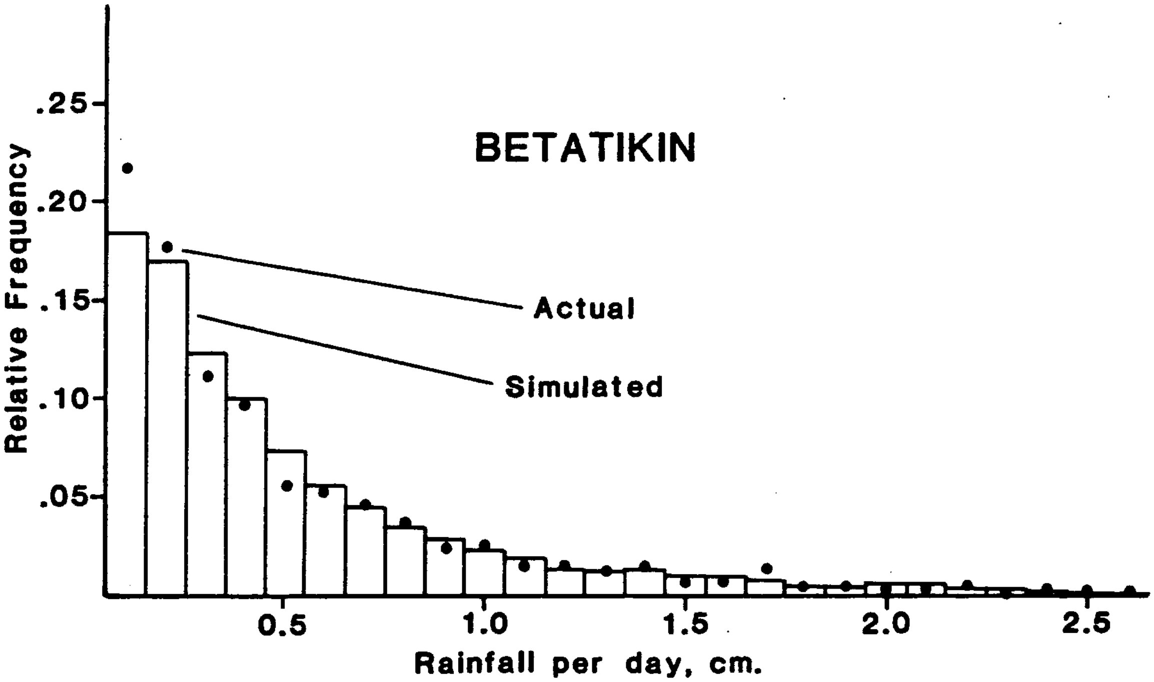


Figure 8. Comparison of actual and simulated probability density functions for rainfall per day at Atterbury and Betatikin.

at a significance level of 0.20. Actual and simulated PDF's of Atterbury results were somewhat less in agreement with actual data than Betatikin. The lower segments of daily interarrival times and daily rainfall amounts (Figures 7 and 8) were rejected at a significance level of 0.01 using the Kolmogorov-Smirnov test (Lingren, 1976). However, goodness of fit for daily rainfall amounts greater than 0.4 cm. could not be rejected at a significance level of 0.05.

Failure of simulated rainfall amounts to agree with actual amounts was probably caused by a lack of information necessary to estimate the amount per thunderstorm cell and per frontal event. Atterbury actual data also shows greater relative variability in its rainfall characteristics than Betatikin (Table 3). This greater variability increases the probability of failing to fit actual data with long-term simulated data.

Simulated and actual data for Atterbury and Betatikin showed a comparable range of values. The range of simulated and actual daily rainfall amounts for Atterbury were 0.1 to 10.1 cm. and 0.1 to 6.8 cm., respectively. The range of simulated and actual daily rainfall amounts for Betatikin were 0.1 to 7.9 cm. and 0.1 to 5.1 cm., respectively. These values indicate the model can generate extreme events comparable to historical records, and will produce greater than recorded events for long-term simulations.

Failure of simulated daily interarrival times to fit actual data for both Atterbury and Betatikin indicates a decided shortage of events having interarrival times of one to seven days (Figures 7 and 8). Failure to reproduce short daily interarrival times (<7 days), is a strong indication of a lack of sufficient persistence of events. The greatest contributor to the lack of persistence is probably the assumption of no persistence for SE storms during formulation of the occurrence model. SE events comprise about 49 percent of all occurences at Atterbury and 16 percent of all occurrences at Betatikin. Inclusion of persistence in simulation of these events could significantly improve the fit of actual and simulated data. Physical processes governing SE moisture indicate the possibility of persistence but further investigation is needed to quantify parameters for inclusion in DROM. Persistence of SW and frontal rainfall may be responsible in part for these shortcomings also. Estimates of persistence as used in DROM may be low and further investigation may justify increasing these parameters.

Although simulated results for Atterbury and Betatikin are not im complete agreement with actual data, the model can be a useful tool. The primary use of SATDOR is modeling extreme rainfall events. SATDOR generates extreme rainfall events at frequencies and magnitudes observed in actual data. Secondarily, SATDOR models seasonal cumulative rainfall comparable to actual data.

SATDOR does not adequately simulate day to day input of rainfall to the hydrologic system, for use in soil moisture estimation, vegetative growth estimation or conjuctive use irrigation scheduling.

SATDOR does adequately simulate extreme events and annual, and seasonal rainfall, for use in drainage design, flood control, and dam and reservior design and operation.

Simulation of Areal Variability of Rainfall

Parameters required by SATDOR to simulate spatial distribution of rainfall events were essentially the same parameters and values described earlier (Table 2). Simulation of areal distributions of rainfall for Atterbury watershed Upper W-1B were performed using the general and site-specific parameters as shown in Table 2, with three exceptions. The location data was changed to represent the center of Upper W-1B watershed (latitude=32.14, longitude=110.77 and elevation=902 m.) rather than the R-2 rain gage. The simulation was was performed for an area including 28.4 km^2. of Upper W-1B and 79.6 km^2. of nearby area surrounding the watershed, totaling 108.0 km^2. The Areal Adjustment Factor, ARAF, was increased to 3.400.

DROM was designed to generate point (<4.0 km^2.) rainfall frequencies. To apply DROM to larger watersheds, an Areal Adjustment Factor, ARAF, was installed in SATDOR. ARAF was explained previously in greater detail. Simulations were performed by SATDOR to calibrate the parameter, ARAF. Fifty years of rainfall records were simulated for Upper W-1B subwatershed using R-2 gage location data. The "best" fit of simulated and actual data occurred for ARAF=3.40. Statistics for the simulated data are averages of data observed at five uniformly distributed sites on Upper W-1B watershed. A comparison of statistics describing the actual and simulated data are shown in Table 4. Analysis of results indicated the simlated data were in agreement with the actual data, however, not as well in agreement as the 500 year simulation at Atterbury (Table 3). Introducing ARAF to SATDOR increased the number of rainfall events occurring in a given area. Since Upper W-1B is substantially larger in area than the points, Atterbury and Betatikin, a substantially greater number of events must be simulated to guarantee the observation of the correct number of events at a particular point on the watershed. For the 50 year simulation, DROM generated an average of 81.1 occurrences per season, resulting in an average of only 23.3 observed rainfall events on Upper W-1B.

Goodness of Fit

After determining the "best" value for ARAF, long-term simulations were performed by SATDOR to subjectively compare the simulated rainfall events with the general characteristics of rainfall events observed in southeastern Arizona. Significant rainfall events (four (4) gage locations >1.5 cm. on a 4.0 km^2. grid) were chosen for the comparisons and examples of these simulated events are shown in Figures 9 and 10. These events were chosen to show the different configurations of storms which produce similar rainfall depths at uniformly distributed gage locations.

The area, shape and magnitude of simulated rainfall events are in general agreement with rainfall events observed in Arizona and New

Table 4. Comparison of statistics of actual and simulated rainfall records at Atterbury R-2 gage and Upper W-1B watershed gages.

Statistical Parameters	Atterbury (R-2 gage) Actual	Upper W-1B (5 gages) Simulated
Mean no. of rainfall events per season	22.9	23.3
Range of no. of rainfall events per season	12-35	14-33
Mean seasonal rainfall (cm.)	15.65	14.20
Minimum seasonal rainfall (cm.)	6.32	5.61
Maximum seasonal rainfall (cm.)	29.92	25.53
Interarrival time between events (days):		
mean	7.34	7.39
variance	139.98	57.51
Rainfall amount per event (cm.):		
mean	0.68	0.61
variance	0.66	0.57

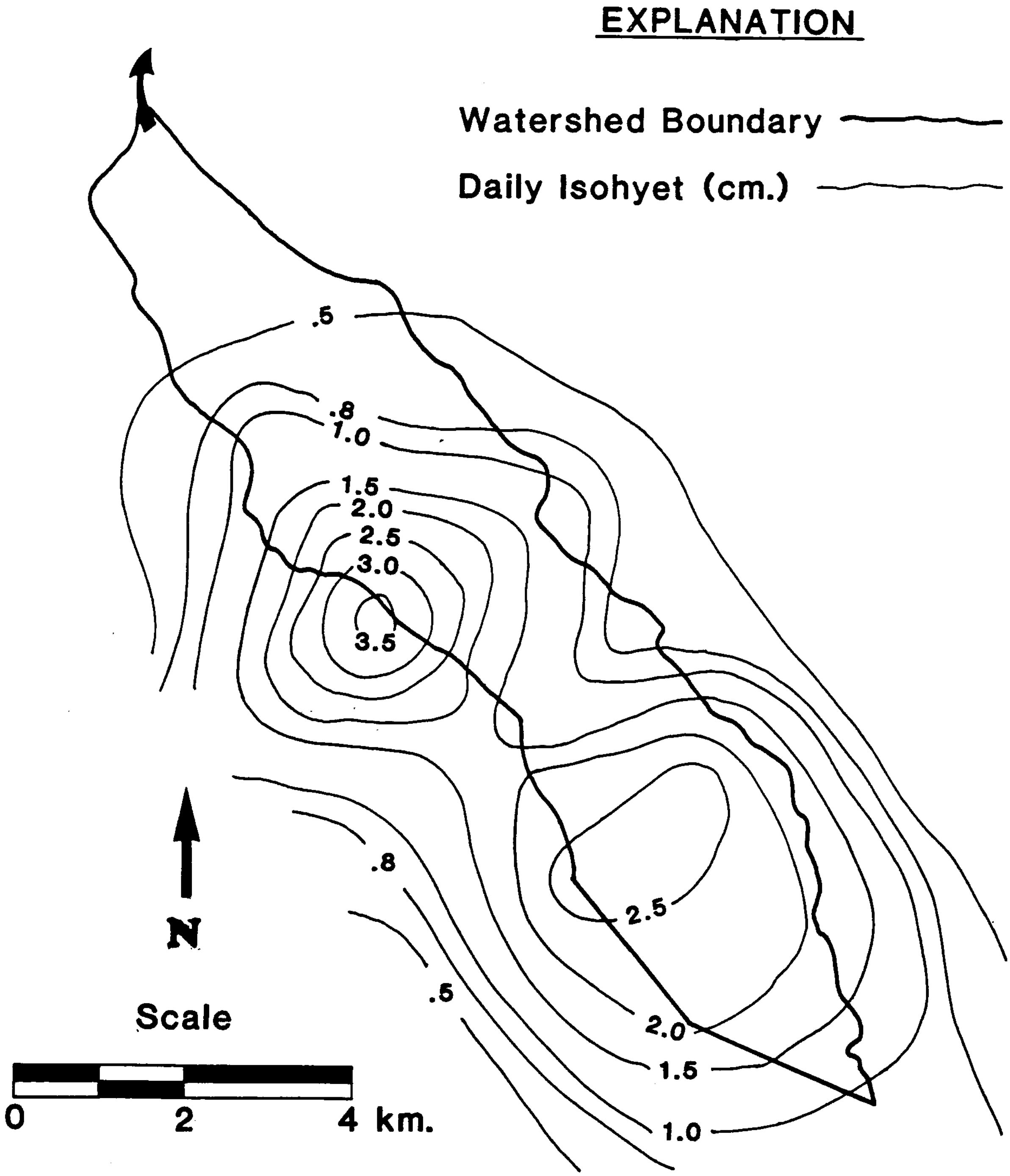


Figure 9. Simulated significant rainfall event over Upper W-1B subwatershed (September 1).

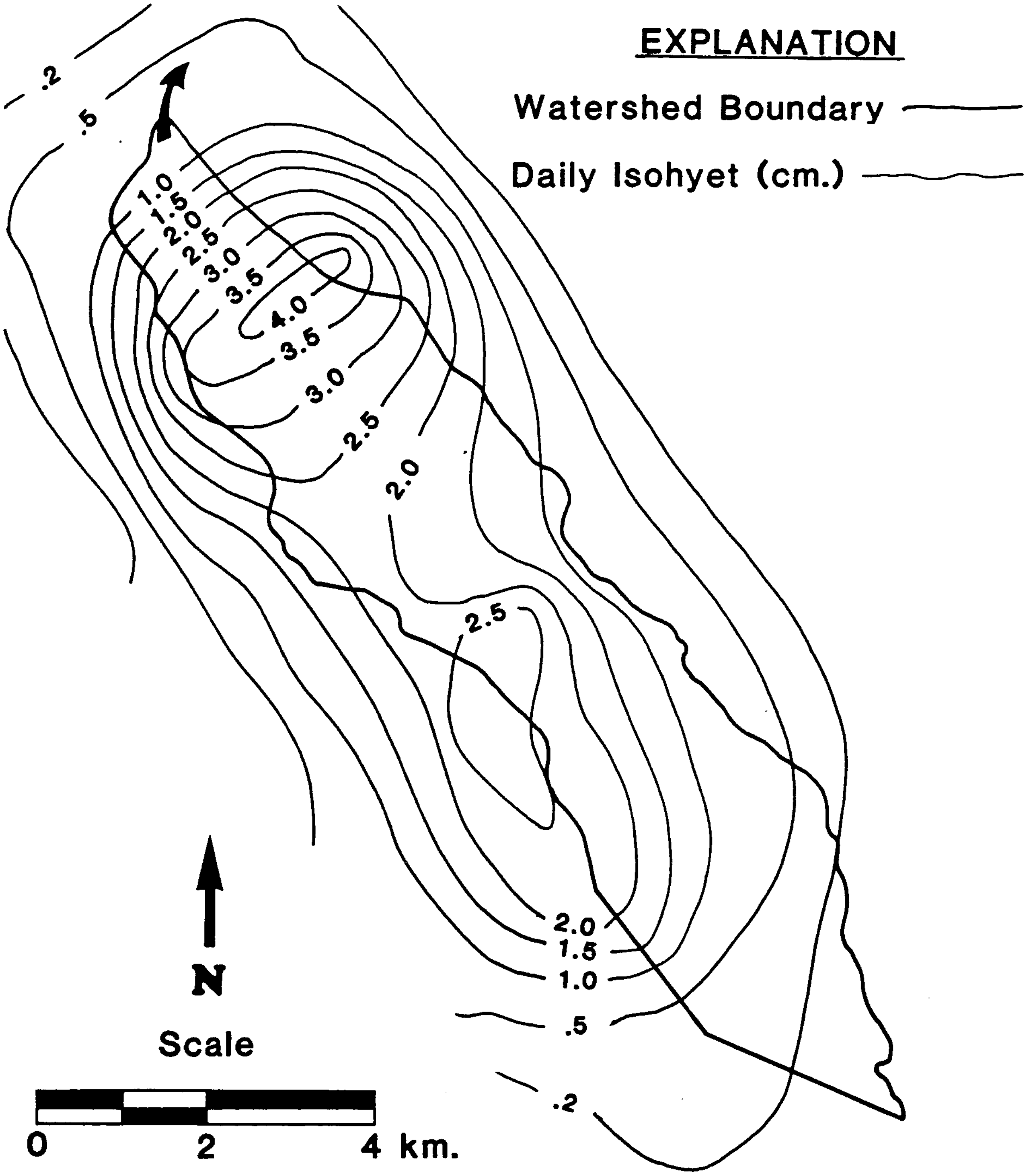


Figure 10. Simulated significant rainfall event over Upper W-1B subwatershed (September 15).

Mexico by researchers discussed in Chapter 2. Amounts observed at two gages near the center of Upper W-1B were 2.5 and 2.0 cm.(September 1) and 2.0 and 2.5 cm.(September 15), respectively. Rainfall amounts observed at these gages are similar but the configuration of the storms are significantly different, with amounts at the other three gage sites being totally dissimilar. These differences illustrate the error introduced into runoff estimates by watershed models when uniform rainfall distributions are used as the rainfall input. This error is especially significant in areas of highly variable rainfall such as Arizona and New Mexico.

Simulation of Runoff Events

Results from SATDOR, simulating individual rainfall events were analyzed and significant events were chosen for simulation of runoff events. Event rainfall results (ie., rainfall depth at locations over the watershed and begin time and duration of rainfall) were selected and rainfall intensity distributions for each event were estimated by a procedure developed by the Bureau of Reclamation, (1973). These rainfall distributions were combined with watershed parameters for Upper W-1B subwatershed to produce input data for the watershed model, HYMO. Watershed parameters used in the runoff simulations are shown in Table 5.

One hundred years of rainfall events were simulated. Several significant events were selected, processed and input into HYMO. Runoff hydrographs were generated for these events. The rainfall

Table 5. Watershed parameters for Upper W-1B subwatershed of Atterbury Experimental Watershed.

Watershed Area:	28.4 km^2.
Watershed Length:	15.5 km.
Change in Elevation:	150.65 m.
Soils Classification:	C/D
Vegetation Type (Density):	Desert Shrub (20%)
Antecedent Moisture Conditions:	I
Runoff Curve Number:	78

events and resulting runoff hydrographs were analyzed to evaluate the watershed response of Upper W-1B. Comparisons were made between the individual rainfall(Figures 9 and 10) and runoff events(Figure 11), indicating differences in runoff characteristics although measured rainfall at gage sites were similar. Peak discharge and total runoff for September 1 was 0.99 cubic meters per second (m^3/s) and 7940 m^3., as compared to 2.76 m^3/s. and 23,100 m^3., for September 15.

Both spatial and temporal distribution of rainfall have a decided effect on the response of watersheds to a rainfall input. Given an adequate spatial distribution of rainfall by SATDOR, the temporal distribution, particularly duration-intensity is a highly sensitive parameter. Slight changes in duration result in large changes in rainfall intensity, the most critical input variable in watershed models. This parameter is especially significant for areas of short duration, high variability storms such as Arizona and New Mexico.

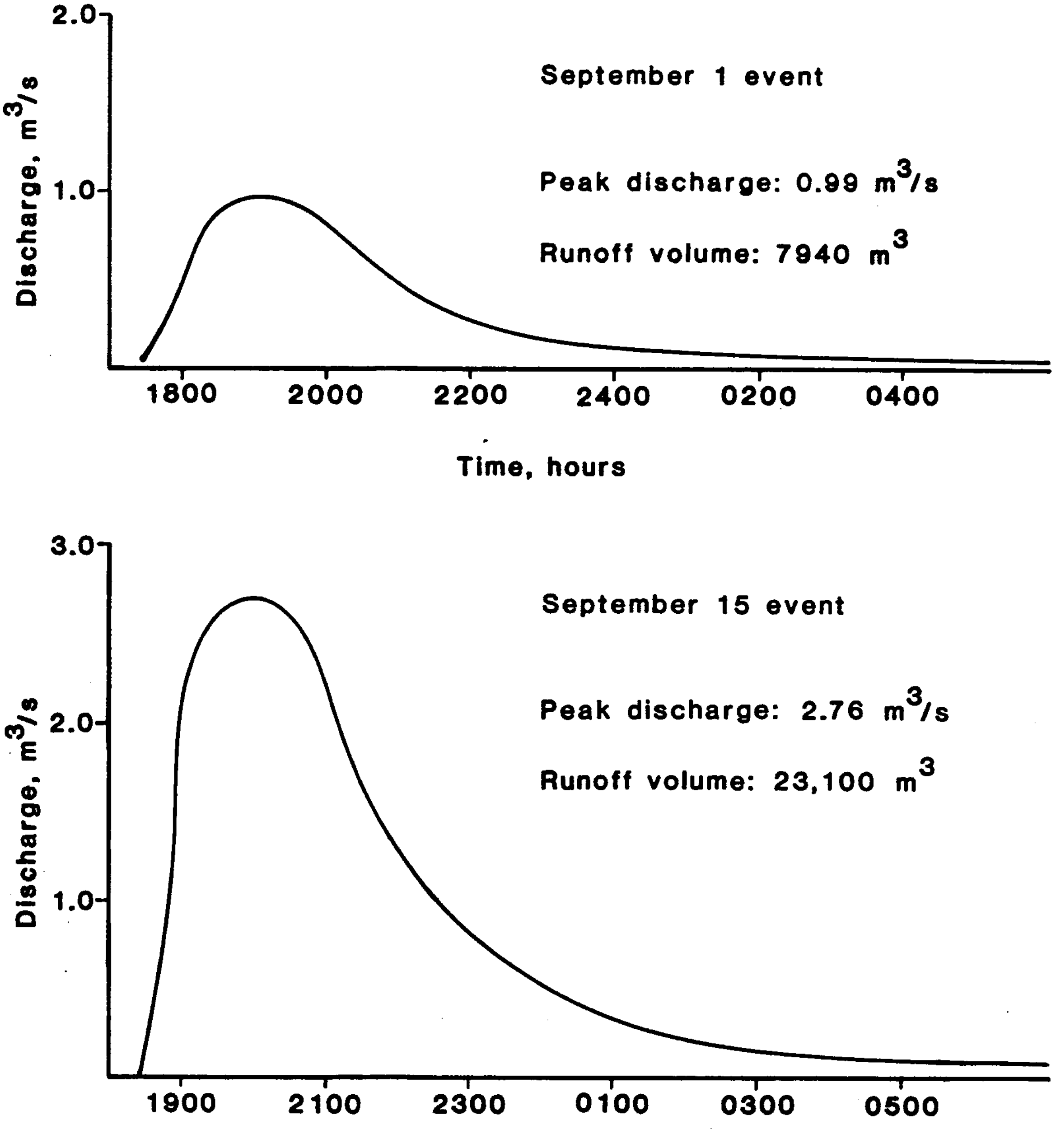


Figure 11. Runoff hydrographs for significant rainfall events (Figures 9 and 10) over Upper W-1B subwatershed.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Procedures were developed for simulating the occurrence, magnitude, and spatial and temporal distribution of runoff-producing rainfall in Arizona and New Mexico. Program SATDOR was developed to give a more accurate representation of the highly variable behavior of rainfall. Improved estimates of rainfall behavior can improve design and analysis of land uses and projects affected by hydrologic considerations.

Program SATDOR simulates the behavior of summer rainfall through a series of stochastic processes. SATDOR was applied to two locations in Arizona. Analysis of simulations indicated that SATDOR adequately reproduces significant rainfall events in an area, however, variations within the results suggest that further calibration of the model be performed, based on regional or local differences. The probability and storm parameters in DROM and SDOR are sensitive to the size of watershed and number of points used to define it. This makes SATDOR less attractive as a rainfall model for regional use. Use of SATDOR generally requires extensive site-specific calibration to provide accurate simulation results. The model can produce reasonable results when used as a regional model but simple calibrations to local conditions improved its performance significantly.

SATDOR is a relatively complex model requiring significant amounts of computer time for execution. Its complexity can limit its usefulness. When linked with a simple watershed model, some of its detailed results are negated. In this investigation, linking SATDOR with HYMO produced runoff simulations that do not completely show the range of variablility of rainfall simulated by SATDOR. HYMO showed that SATDOR could be linked with a watershed model and produce reasonable, useful estimates of runoff. In the future, SATDOR should be linked to a watershed model based on a nodal or grid system, taking full advantage of its spatial distribution capabilities.

SATDOR requires further refinement. Analysis of more extensive precipitation records can lead to improved modeling of persistence processes. Further analysis can also produce improved estimates of parameters used by SATDOR. Sensitivity analysis of the performance of SATDOR may lead to simplifying the model by eliminating or consolidating insensitive processes.

Rainfall duration-intensity is probably the most sensitive stochastic process in SATDOR. It can vary considerably and have a substantial impact on simulation of runoff events. The stochastic process should be modified to generate rainfall duration-intensities that are related to storm depths and its parameters should be analyzed and improved.

APPENDIX A

PROGRAM LISTING OF SATDOR

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      PROGRAM SATDOR1(INPUT,OUTPUT,TAPE3,TAPE4,TAPE5,TAPE1=
     *INPUT,TAPE2=OUTPUT)
C
      COMMON /SEASON/ NYEARS,BEGIN,END,NBEGIN,NEND
      COMMON /MODEL/ DUM1,STORM(365),DUM2,MULTEV(365)
      COMMON /STAT/ RANE(366,5),NN,DGDEP(5),GAGECHK(5)
      COMMON /GAGES/ NGAGES,POINTS(100),GX(100),GY(100),
     *TH(100),INOUT(100)
      COMMON /PRECIP/ GDEPTHS(100)
      INTEGER BEGIN,END,STORM,GAGECHK,POINTS
      DATA RANE/1830*0.0/
C
C   READ IN GAGE LOCATIONS AND ESTABLISH WATERSHED BOUNDARIES
C
      CALL WSHED
C
C   READ IN PARAMETERS FOR PRECIPITATION OCCURRENCE MODEL
C
      CALL PDF
C
C   READ IN SPATIAL AND TEMPORAL DISTRIBUTION PARAMETERS
C
      CALL SPAR
      CALL TPAR
C
C   GENERATE A SIMULATED PRECIPITATION RECORD
C
      DO 2000 NYR=1,NYEARS
C
C   GENERATE ONE YEAR OF RAINFALL OCCURRENCE DATA
C
      BEGIN=NBEGIN  $  END=NEND
      JCK=MOD(NYR,4)
      IF(JCK.NE.0) GOTO 2100
      BEGIN=NBEGIN+1  $  END=NEND+1
2100  CALL DROM
C
C   GENERATE DAILY RAINFALL FOR ONE YEAR OF OCCURRENCE DATA
C
      DO 3000 I=BEGIN,END
      DO 3001 NG=1,NN
3001  DGDEP(NG)=0.0
      IF(STORM(I).EQ.0) GOTO 3002
C
C   SIMULATE THE SPATIAL DISTRIBUTION OF EACH RAINFALL EVENT
C   GENERATE THE BEGIN AND END TIMES FOR EACH RAINFALL EVENT
C
      CALL SDOR(I)
C
C   COMPILE THE  RAINFALL RECORD FOR ONE SEASON AT NN GAGES
C
      DO 3003 NG=1,NN
3003  IF(DGDEP(NG).LT.0.0254) DGDEP(NG)=0.0
3002  DO 3004 NG=1,NN
3004  RANE(I,NG)=DGDEP(NG)
3000  CONTINUE
      DO 3005 NG=1,NN
      WRITE(2,901) NYR,GAGECHK(NG)
      WRITE(2,902) (RANE(I,NG),I=BEGIN,END)
3005  WRITE(3,903) (RANE(I,NG),I=BEGIN,END)
      WRITE(5,904) (STORM(I),I=BEGIN,END)
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
2000  CONTINUE
901   FORMAT(//," YEAR - ",I3,T25,"GAGE LOCATION - ",I3,/)
902   FORMAT(" ",16(F8.4))
903   FORMAT(20F7.4)
904   FORMAT(30I2)
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE WSHED
C
      COMMON /STAT/ RAME(366,5),NN,DGDEP(5),GAGECHK(5)
      COMMON /GAGES/ NGAGES,POINTS(100),GX(100),GY(100),
     *TH(100),INOUT(100)
      COMMON /RECT/ DELX,DELY,XL,YL
      COMMON /BASEPSE/ PSE(365),ARAF,PROB2,PROB3,SWPER,
     *FRPER,PRAF
      INTEGER GAGECHK,POINTS
      XL=YL=1.E6 $ XU=YU=0.0
C
      READ(1,800) NN,ARAF,(GAGECHK(N),N=1,NN)
      N=1
1     READ(1,801) POINTS(N),INOUT(N),GX(N),GY(N),TH(N)
      IF(EOF(1)) 2,5
5     XL=AMIN1(XL,GX(N)) $ YL=AMIN1(YL,GY(N))
      XU=AMAX1(XU,GX(N)) $ YU=AMAX1(YU,GY(N))
      N=N+1
      GOTO 1
2     NGAGES=N-1
      IF(NGAGES.EQ.0.0) STOP"GAGES MISSING"
      WRITE(4,903) NGAGES,XL,XU,YL,YU
      DELX=XU-XL $ DELY=YU-YL
      AREA=DELX*DELY
C
C   SET BUFFER ZONE  AT 1.0 KM. FOR "LARGE" WATERSHEDS
C   ( >4.0 SQ. KM.)
C   SET BUFFER ZONE AT 4.0 KM. FOR "POINT" SIMULATIONS
C   ( 4.0 SQ. KM.)
C
      XL=XL-1.0 $ XU=XU+1.0
      YL=YL-1.0 $ YU=YU+1.0
      DELX=XU-XL $ DELY=YU-YL
      AREAB=DELX*DELY
      WRITE(2,900)(POINTS(N),INOUT(N),GX(N),GY(N),TH(N),N=1,
     *NGAGES)
      WRITE(2,901)(GAGECHK(N),N=1,NN)
      WRITE(2,902)AREA,ARAF
      WRITE(4,904)(POINTS(I),INOUT(I),GX(I),GY(I),TH(I),I=1,
     *NGAGES)
      RETURN
800   FORMAT(I10,F10.3,5I10)
801   FORMAT(2I10,3F10.3)
900   FORMAT("1",5(/),40X,"LOCATION POINTS USED TO DEFINE ",
     *"WATERSHED BOUNDARIES",5(/),7X,"POINTS",3X,"INOUT",3X,
     *"X-ORDINATE",3X,"Y-ORDINATE",3X,"TH. WEIGHT",9X,
     *"POINTS",3X,"INOUT",3X,
     *"X-ORDINATE",3X,"Y-ORDINATE",3X,"TH. WEIGHT",3(/),
     *3(/),2(8X,I3,7X,I2,
     *5X,F7.4,6X,F7.4,7X,F6.4,4X))
901   FORMAT(" ",///,13X,"THE HISTORICAL RAINFALL RECORD ",
     *"WILL BE CHECKED AGAINST THE SIMULATED RECORD",
     *" AT POINTS",5(I3,","))
902   FORMAT(" ",5(/),T12,"THE AREA OF THE WATERSHED IS ",
     *F8.3,"SQUARE KILOMETERS",15X,"AREAL ADJUSTMENT",
     *" FACTOR = ",F5.3)
903   FORMAT(I10,1X,F6.3,1X,F6.3,1X,F6.3,1X,F6.3)
904   FORMAT(I3,1X,I2,1X,F6.3,1X,F6.3,1X,F6.3)
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE PDF
C
      COMMON /SEASON/ NYEARS,BEGIN,END,NBEGIN,NEND
      COMMON /SITE/ REGION,LAT,LONG,HIGHT
      COMMON /BASEPSE/ PSE(365),ARAF,PROB2,PROB3,SWPER,
     *FRPER,PRAF
      COMMON /MODEL/ DUM1,STORM(365),DUM2,MULTEV(365)
      INTEGER BEGIN,END,REGION,STORM
      REAL LAT,LONG
C
      READ(1,800) NYEARS,NBEGIN,NEND
      READ (1,801) REGION,LAT,LONG,HIGHT
      READ (1,802) PROB2,PROB3,SWPER,FRPER,PRAF
      WRITE(2,900) REGION,LAT,LONG,HIGHT
      WRITE(2,901) PROB2,PROB3,SWPER,FRPER,PRAF
900   FORMAT(" ",7(/),43X,"LOCATION OF CENTER OF WATERSHED",
     *///,28X,"REGION",10X,"LATITUDE",10X,"LONGITUDE",10X,
     *"ELEVATION",/,44X,"(DEGREES)",9X,"(DEGREES)",10X,
     *"(METERS)",///,30X,I1,13X,F7.2,12X,F7.2,11X,F8.2)
901   FORMAT(" ",7(/),42X," STORM TYPE PROBABILITIES",///,
     *10X,"SECOND AND THIRD THUNDERSTORM",10X,"PERSISTENCE",
     *" OF SW AND FRONTAL",10X,"PROBABILITY ADJUSTMENT "
     *"FACTOR",//,19X,F5.4,",",F5.4,28X,F5.4,",",F5.4,
     *30X,F6.4)
C
C  CONVERT ELEVATION IN METERS TO FEET (FOR USE BY DROM)
C
      HIGHT=HIGHT*3.281

      IF (REGION.EQ.3) GOTO 2
      IF (REGION.EQ.2) GOTO 1
      READ (1,803)PSE,DUMMY
      RETURN
    1 READ (1,804) PSE,DUMMY
      RETURN
    2 READ (1,805) PSE
      RETURN
800   FORMAT(3I5)
801   FORMAT(I5,3F10.3)
802   FORMAT(5F10.8)
803   FORMAT(14(25F3.2/),15F3.2,30(/),A1)
804   FORMAT(15(/),14(25F3.2/),15F3.2,15(/),A1)
805   FORMAT(30(/),14(25F3.2/),15F3.2)
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE SPAR
C
      COMMON /THPRE/ TYPE(8),ANOC(8),ADEP(8),ARAD(8)
      COMMON /FPRE/ DEPTH,FRLAM,FRKK
C
C   READ AND PRINT SPATIAL DISTRIBUTION PARAMETERS
C
      READ(1,800) (TYPE(N),ANOC(N),ADEP(N),ARAD(N),N=1,8)
      READ(1,801) FRMEAN,FRVAR
      WRITE(2,900) (TYPE(N),ANOC(N),ADEP(N),ARAD(N),N=1,8)
      WRITE(2,901) FRMEAN,FRVAR
      FRLAM=FRMEAN/FRVAR
      FRKK=FRLAM*FRMEAN
      RETURN
800   FORMAT(I1,9X,3F10.5)
801   FORMAT(2F10.7)
900   FORMAT("1",5(/),T45,"SPATIAL DISTRIBUTION PARAMETERS",
     *5(/),T31,"FOR CALCULATION OF DEPTH OF RAINFALL FROM",
     *" THUNDERSTORMS",4(/),30X,"STORM",14X,"AVERAGE",13X,
     *"AVERAGE",13X,"AVERAGE",/,31X,"TYPE",12X,
     *"NO. OF CELLS",8X,"CENTER DEPTH",11X,"RADIUS",
     */,63X,"(CM.)",15X,"(KM.)",///,
     *7(32X,I1,2X,3F18.3,//))
901   FORMAT(" ",3(/),30X,"FOR CALCULATION OF DEPTH OF RAIN"
     *" FALL FROM FRONTAL EVENTS",4(/),41X,"STATISTICS FOR "
     *"DEPTH PER FRONTAL EVENT",///,41X,"MEAN",25X,
     *"VARIANCE",/,41X,"(CM.)",27X,"(CM.)",//,40X,F6.3,
     *26X,F6.3)
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE TPAR
C
      COMMON /THTIME/ THM1,THM2(2),THM3(3),THSD(3),ELAM(2),
     *EK(2)
      DIMENSION EMEAN(2),EVAR(2)
C
C   READ AND PRINT TEMPORAL DISTRIBUTION PARAMETERS
C
      READ(1,800) THM1,THSD(1),THM2(1),THM2(2),THSD(2),
     *THM3(1),THM3(2),THM3(3),THSD(3)
800   FORMAT(9F7.5)
      READ(1,801) EMEAN(1),EVAR(1),EMEAN(2),EVAR(2)
801   FORMAT(4F10.7)
      WRITE(2,902)
      N=1
      WRITE(2,903) N,THM1,THSD(N)
      N=2
      WRITE(2,903) N,THM2(1),THSD(N),THM2(2),THSD(N)
      N=3
      WRITE(2,903) N,THM3(1),THSD(N),THM3(2),THSD(N),
     *THM3(3),THSD(N)
      WRITE(2,904) EMEAN(1),EVAR(1)
      WRITE(2,905) EMEAN(2),EVAR(2)
      DO 1 I=1,2
      ELAM(I)=EMEAN(I)/EVAR(I)
1     EK(I)=ELAM(I)*EMEAN(I)
C
902   FORMAT("1",4(/)/,44X,"TEMPORAL DISTRIBUTION ",
     *"PARAMETERS",4(/),
     *38X,"FOR BEGINNING TIME AND DURATION OF ",
     *"THUNDERSTORMS",4(/),
     *T40,"STATISTICS FOR BEGINNING TIME PER ",
     *"NUMBER",10X,"STORM 1",9X,"STORM 1",9X,"STORM 2",9X,
     *"STORM 2",9X," THUNDERSTORM",///,9X,
     *"STORM 3",9X,"STORM 3",/,8X,"OF STORMS",9X,"MEAN",10X,
     *"STD.DEV.",10X,"MEAN",10X,"STD.DEV.",10X,"MEAN",10X,
     *"STD.DEV.",/,9X,"PER DAY",9X,"(HRS.)",10X,"(HRS.)",10X
     *,"(HRS.)",10X,"(HRS.)",10X,"(HRS.)",10X,"(HRS.)",///)
903   FORMAT("0",11X,I1,12X,F6.3,11X,F5.3,10X,F6.3,11X,F5.3,
     *10X,F6.3,11X,F5.3)
904   FORMAT(" ",4(/),T40,"STATISTICS FOR THUNDERSTORM"
     *"DURATION",
     *"(STORM(1-3))",///,38X,"MEAN",40X,
905   FORMAT(" ",///,T37,"STATISTICS FOR EXTREME "
     *"THUNDERSTORM DURATION","(STORM(5-7))",///,38X,"MEAN",
     *40X,"VARIANCE",//,35X,F6.4,40X,F6.4)
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE DROM
C
C  DROM (DAILY RAINFALL OCCURRENCE MODEL)
C
C  DROM GENERATES A RAINFALL OCCURRENCE RECORD FOR A
C  LOCATION AND ELEVATION.  THE OCCURRENCE RECORD REFLECTS
C  THE PROBABILITY OF F,SE,SW OR COMBINATION STORMS.
C
      COMMON /SEASON/ NYEARS,BEGIN,END,NBEGIN,NEND
      COMMON /SITE/ REGION,LAT,LONG,HIGHT
      COMMON /BASEPSE/ PSE(365),ARAF,PROB2,PROB3,SWPER,
     *FRPER,PRAF
N-12  COMMON /MODEL/ DUM1,STORM(365),DUM2,MULTEV(365)
      DIMENSION SYMBOL(8)
      INTEGER BEGIN,END,REGION,STORM,SYMBOL
      REAL    LAT,LONG
      DATA SYMBOL/" "," SE","    SW"," SE SW","       F",
     *" SE    F","    SW F"," SE SW F"/
C
    3 DO 4 J=BEGIN,END
    4 STORM(J)=0
C
C  CHOOSE THE MOISTURE TYPE SUBROUTINES.
C
      CALL SE
      CALL SW
      CALL FRONTAL
C
C     PREDICT MULTIPLE EVENTS FOR SE,SW
C
      DO 10 J=BEGIN,END
      MULTEV(J)=0
      IF(STORM(J).EQ.0.O.STORM(J).EQ.4) GOTO 10
      MULTEV(J)=1
      IF(RANF(J).GT.PROB2) GOTO 10
      MULTEV(J)=2
      IF(RANF(J).GT.PROB3) GOTO 10
      MULTEV(J)=3
10    CONTINUE
C
C  PRINT OUT THE RESULTS
C
      WRITE(2,806) REGION,HIGHT,LAT,LONG,(N,MULTEV(N),
     *SYMBOL(STORM(N)+1),N=BEGIN,END)
806   FORMAT(1H1,2X,"DAILY RAINFALL OCCURRENCES FOR A "
     *"WATERSHED IN REGION",I2," WITH ELEVATION",F8.2,
     *", LATITUDE",F7.2," AND LONGITUDE",F7.2,2(/),
     *6("  DAY  NO.    TYPES  "),/,6(I5,3X,I1,2X,A8,1X))
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE SE
C
      COMMON /SEASON/ NYEARS,BEGIN,END,NBEGIN,NEND
      COMMON /SITE/ REGION,LAT,LONG,HIGHT
      COMMON /BASEPSE/ PSE(365),ARAF,PROB2,PROB3,SWPER,
     *FRPER,PRAF
      COMMON /MODEL/ DUM1,STORM(365),DUM2,MULTEV(365)
      INTEGER BEGIN,END,REGION,STORM
      REAL    LAT,LONG
C
C   SE STORM OCCURRENCE ON DAY N (BEGIN.LE.END) IS DESCRIBED
C   BY PROBABILITY P(N) THAT IS CALCULATED BY:
C
C   P(N)=PSE(N)*R(WATERSHED SITE)*ARAF(AREAL ADJUSTMENT
C        FACTOR)*PRAF(PROBABILITY ADJUSTMENT FACTOR)
C
C   PSE(N)= PROBABILITY OF AN AIR-MASS THUNDERSTORM OCCURRING
C           ON DAY N AT THE BASE SITE OF  REGION CONTAINING
C           WATERSHED BEING MODELED.  THE VALUES ARE ESTIMATED
C           FROM DATA AT THE BASE SITE AND READ INTO AN ARRAY.
C   R(---)= FACTOR TO COMPENSATE FOR THE WATERSHED NOT BEING
C           AT THE BASE SITE. THIS IS EXPRESSED AS A FUNCTION
C           OF THE WATERSHED SITE. THE COEFFICIENTS ARE
C           ESTIMATED FROM OTHER DATA IN THE REGION.
C
C     REGION 1   R=1.218+.10(33.4-LAT)-.11((3640-HIGHT)/1000)
C     REGION 2   R=.65+.10(32.4-LAT)-.02((3880-HIGHT)/1000)
C     REGION 3   R=.67+.08(31.5-LAT)-.09((4100-HIGHT)/1000)
C
C   THIS ROUTINE SETS BIT 1 OF STORM(N) TO 1 P(N) PERCENT
C   OF THE TIME IT IS CALLED TO MODEL THE OCCURRENCE OF SE
C   STORMS.
C
      IF (REGION.EQ.2) GOTO 2
      IF (REGION.EQ.3) GOTO 3
C
C  REGION 1 CALCULATION OF R
C
      R=4.158-.1*LAT+.11*HIGHT/1000
      GOTO 10
C
C  REGION 2 CALCULATION OF R
C
    2 R=3.812-.1*LAT+.02*HIGHT/1000
      GOTO 10
C
C  REGION 3 CALCULATION OF R
C
    3 R=2.821-.08*LAT+.09*HIGHT/1000.
C
C  SET BIT 1 BASED UPON PSE(N)*R*ARAF*PRAF
C
   10 DO 20 N=BEGIN,END
      IF (RANF(N).LT.PSE(N)*R*ARAF*PRAF)
     * STORM(N)=STORM(N).O.1
   20 CONTINUE
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE SW
C
      COMMON /SEASON/ NYEARS,BEGIN,END,NBEGIN,NEND
      COMMON /SITE/ REGION,LAT,LONG,HIGHT
      COMMON /BASEPSE/ PSE(365),ARAF,PROB2,PROB3,SWPER,
     *FRPER,PRAF
      COMMON /MODEL/ DUM1,STORM(365),DUM2,MULTEV(365)
      INTEGER BEGIN,END,REGION,STORM
      REAL    LAT,LONG
C
C   SW STORM OCCURRENCE ON DAY N (BEGIN.LE.END) IS DESCRIBED
C   BY A PROBABILITY P(N) WHICH IS CONDITIONAL ON RAINFALL
C   THAT OCCURRED ON THE PREVIOUS DAY.
C
C   IF PREVIOUS DAY HAS NO SW MOISTURE (ASSUME NONE ON
C   BEGIN-1)
C
C    P(N)=PFIRST=MAX(0,.064+.000008*HIGHT+.009(31-LAT)
C                 -.01(115-LONG)*ARAF*PRAF
C
C   IF THE PREVIOUS DAY HAS SW MOISTURE
C
C    P(N)=PMULTI*MIN(SWPER,PFIRST*HIGHT/1000)
C
C   THIS ROUTINE SETS BIT 2 OF STORM(N) TO 1 P(N) PERCENT
C   OF THE TIME IT IS CALLED TO MODEL THE OCCURRENCE OF SW
C   STORMS.
C
C
C     P(N), NO PRIOR SW STORM
C
      PFIRST=AMAX1(0.,(-.776+.000008*HIGHT-.009*LAT
     *+.01*LONG)*ARAF*PRAF)
C
C     P(N), PRIOR SW STORM
C
C
C   SET BIT 2 BASED UPON PFIRST AND PMULTI
C
      LAST=0
      DO 3 N=BEGIN,END
      X=RANF(N)
      IF (LAST.EQ.1) GOTO 1
      IF (X.GE.PFIRST) GOTO 3
      LAST=1 $ STORM(N)=STORM(N).O.2B
      PMULTI=AMIN1(SWPER,PFIRST*HIGHT/1000.) $ GOTO 3
    1 IF (X.GE.PMULTI) GOTO 2
      STORM(N)=STORM(N).O.2B
      PMULTI=SWPER*PMULTI $ GOTO 3
    2 LAST=0
    3 CONTINUE
      RETURN
      END
```

```
SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)
      SUBROUTINE FRONTAL
C
      COMMON /SEASON/ NYEARS,BEGIN,END,NBEGIN,NEND
      COMMON /SITE/ REGION,LAT,LONG,HIGHT
      COMMON /BASEPSE/ PSE(365),ARAF,PROB2,PROB3,SWPER,
     *FRPER,PRAF
      COMMON /MODEL/ DUM1,STORM(365),DUM2,MULTEV(365)
      INTEGER BEGIN,END,REGION,STORM
      REAL    LAT,LONG
C
C  F STORM OCCURRENCE ON DAY N (BEGIN.LE.END) IS DESCRIBED
C  BY A PROBABILITY P(N) WHICH IS CONDITIONAL ON THE RAINFAL
C  THAT OCCURRED ON THE PREVIOUS DAY.
C
C   IF PREVIOUS DAY HAS NO F MOISTURE (ASSUME NONE ON
C   BEGIN-1)
C
C   P(N)=PFIRST=MAX(0,.10+.005 (101-LONG)-.01(36-LAT))*PRAF
C
C    IF PREVIOUS DAY HAS F MOISTURE
C
C   P(N)=PMULTI=MIN(FRPER,PFIRST*HIGHT/1000)
C
C  THIS ROUTINE SET BIT 3 OF STORM(N) TO 1 P(N) PERCENT
C  OF THE TIME IT IS CALLED TO MODEL THE OCCURRENCE OF FRONT
C  STORMS.
C
C    P(N), NO PRIOR FRONTAL STORM
C
      PFIRST=AMAX1(0.,(.245-.005*LONG +.01*LAT)*PRAF)
C
C    P(N), PRIOR FRONTAL STORM
C
C  SET BIT 3 BASED UPON PFIRST AND PMULTI
C
      LAST=0
      DO 3 N=BEGIN,END
      X=RANF(N)
      IF (LAST.EQ.1) GOTO 1
      IF (X.GE.PFIRST) GOTO 3
      LAST=1 $ STORM(N)=STORM(N).O.4B
      PMULTI=AMIN1(FRPER,PFIRST*HIGHT/1000.)  $  GOTO 3
    1 IF (X.GE.PMULTI) GOTO 2
      STORM(N)=STORM(N).O.4B
      PMULTI=FRPER*PMULTI $ GOTO 3
    2 LAST=0
    3 CONTINUE
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE SDOR(I)
C
C   SDOR (SPATIAL DISTRIBUTION OF RAINFALL)
C
C   THIS SUBROUTINE SPATIALLY DISTRIBUTES RAINFALL THAT
C   OCCURS FOR EACH RAINFALL EVENT PRODUCED BY DROM. IT PRINT
C   LOCATION AND DEPTH OF RAINFALL FOR EACH EVENT.
C
      COMMON /MODEL/ DUM1,STORM(365),DUM2,MULTEV(365)
      COMMON /THPRE/ TYPE(8),ANOC(8),ADEP(8),ARAD(8)
      COMMON /FPRE/ DEPTH,FRLAM,FRKK
      COMMON /GAGES/ NGAGES,POINTS(100),GX(100),GY(100),
     *TH(100),INOUT(100)
      COMMON /PRECIP/ GDEPTHS(100)
      COMMON /CELLS/ NOC,CX(20),CY(20),RAD(20),CELDEP(20)
      COMMON /STAT/ RANE(366,5),NN,DGDEP(5),GAGECHK(5)
      INTEGER STORM,TYPE,GAGECHK,POINTS
      DATA DEPTH,NOC /0.0,0/
C
C   CHOOSE THE PROPER SET OF STORM CALCULATIONS BASED ON THE
C   TYPE OF OCCURRENCE FOR THAT EVENT
C
      ITYPE=STORM(I)+1
      GOTO (1000,100,100,100,200,300,300,300) ITYPE
C
C   CALCULATIONS FOR THUNDERSTORMS-SE,SW,SESW
C
100   J=ITYPE
      K=MULTEV(I)
      DO 110 L=1,K
      CALL DTHUND(J)
      N=1
      KOUNT=0
115   IF(N.EQ.NGAGES) GOTO 118
      IF(GDEPTHS(N).GT.1.5) GOTO 116
      N=N+1
      GOTO 115
116   KOUNT=KOUNT+1
      N=N+1
      IF(KOUNT.LT.4) GOTO 115
      CALL TDOR(I,L)
      CALL PRINTER(I,J,L)
118   NOC=0
      DO 120 N=1,NN
120   DGDEP(N)=DGDEP(N)+GDEPTHS(N)
      DO 110 N=1,NGAGES
110   GDEPTHS(N)=0.0
      RETURN
C
C   CALCULATIONS FOR FRONTAL EVENTS-F
C
200   J=ITYPE
      K=MULTEV(I)
      L=1
      CALL DFRONT(J)
      KOUNT=0
      DO 215 N=1,NGAGES
      IF(GDEPTHS(N).GT.1.5) GOTO 216
215   CONTINUE
      GOTO 218
216   KOUNT=KOUNT+1
```

```
      IF(KOUNT.LT.4) GOTO 218
      CALL TDOR(I,L)
      CALL PRINTER(I,J,L)
218   NDC=0
      DO 220 N=1,NN
220   DGDEP(N)=GDEPTHS(N)
      DO 210 N=1,NGAGES
210   GDEPTHS(N)=0.0
       RETURN
C
C  CALCULATIONS FOR FRONTAL AND THUNDERSTORM EVENTS-FSE,FSW,
C  FSESW
C
C  COMPUTE THE FRONTAL DEPTH
C
300   J=ITYPE
      K=MULTEV(I)
      L=1
      CALL DFRONT(J)
C
C  COMPUTE THUNDERSTORM DEPTHS
C
      DO 310 L=1,K
      CALL DTHUND(J)
      N=1
      KOUNT=0
315   IF(N.EQ.NGAGES) GOTO 318
      IF(GDEPTHS(N).GT.1.5) GOTO 316
      N=N+1
      GOTO 315
316   KOUNT=KOUNT+1
      N=N+1
      IF(KOUNT.LT.4) GOTO 315
      CALL TDOR(I,L)
      CALL PRINTER(I,J,L)
318   DEPTH=0.0
      NDC=0
      DO 320 N=1,NN
320   DGDEP(N)=DGDEP(N)+GDEPTHS(N)
      DO 310 N=1,NGAGES
310   GDEPTHS(N)=0.0
1000  RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE DTHUND(J)
C
C  DTHUND GENERATES SPATIALLY DISTRIBUTED THUNDERSTORM
C  RAINFALL BY CREATING A RANDOM SERIES OF CIRCULAR RAIN
C  CELLS WHICH MOVE ACROSS A WATERSHED. IT DISTRIBUTES
C  RAINFALL DEPTHS WITHIN THE CELLS. THE SUM OF THE CELL
C  DEPTHS AT THE RAIN GAGES GIVES THE TOTAL DEPTH.
C
      COMMON /GAGES/ NGAGES,POINTS(100),GX(100),GY(100),
     *TH(100),INOUT(100)
      COMMON /PRECIP/ GDEPTHS(100)
      COMMON /CELLS/ NOC,CX(20),CY(20),RAD(20),CELDEP(20)
      COMMON /STAT/ RANE(366,5),NN,DGDEP(5),GAGECHK(5)
      INTEGER GAGECHK,POINTS
      DATA GDEPTHS/100*0.0/
C
C  GENERATE THE NUMBER OF CELLS PER STORM
C
      CALL NOCS(J)
C
C  GENERATE DIRECTION AND DISTANCE FOR MOVEMENT OF CELLS
C
1     CALL DIRDIST(J)
C
C  CHECK TO SEE IF THE STORM AREA TOUCHES THE WATERSHED
C
      DO 10 NG=1,NGAGES
      IF(INOUT(NG).EQ.0) GOTO 10
      DO 5 NC=1,NOC
      X=CX(NC)-GX(NG)
      Y=CY(NC)-GY(NG)
5     IF(X*X+Y*Y.LT.RAD(NC)*RAD(NC)) GOTO 20
10    CONTINUE
      GOTO 1
C
C  GENERATE THE DEPTH OF RAINFALL FOR EACH CELL
C
20    CALL CDEPTH(J)
C
C  CUMULATE RAINFALL DEPTH AT EACH GAGE FROM ALL CELLS
C
      DO 50 NG=1,NGAGES
      DO 50 NC=1,NOC
      GDEPTHS(NG)=GDEPTHS(NG)+GCDEPTH(NG,NC)
50    CONTINUE
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE NOCS(J)
C
C   NOCS GENERATES A PSEUDO-RANDOM NUMBER OF CELLS FOR ONE
C   THUNDERSTORM USING IMSL LIBRARY SUBROUTINE GGPOS.
C
      COMMON /CELLS/ NOC,CX(20),CY(20),RAD(20),CELDEP(20)
      COMMON /THPRE/ TYPE(8),ANOC(8),ADEP(8),ARAD(8)
      INTEGER TYPE
C
      X=ANOC(J)
1     CALL GGPOS (X,234.D0,1,NOC,IER)
      IF(NOC.LT.3.OR.NOC.GT.20) GOTO 1
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE DIRDIST(J)
C
C  DIRDIST GENERATES THE LOCATION OF CENTERS OF RAIN CELLS
C  AND THE PATH OF MOVEMENT OF THE CELLS.
C
      COMMON /CELLS/ NOC,CX(20),CY(20),RAD(20),CELDEP(20)
      COMMON /RECT/ DELX,DELY,XL,YL
      COMMON /THPRE/ TYPE(8),ANOC(8),ADEP(8),ARAD(8)
      INTEGER TYPE
C
      CX(1)=XL+DELX*RANF(J)
      CY(1)=YL+DELY*RANF(J)
      RAD(1)=ARAD(J)
      ANGLE=6.2831853*RANF(1)
C
      DO 1 NC=2,NOC
      D=DIST(J)
      CX(NC)=D*COS(ANGLE)+CX(NC-1)
      CY(NC)=D*SIN(ANGLE)+CY(NC-1)
      RAD(NC)=ARAD(J)
      SND=GGNQF(234.D0)/3.
      ANGLE=ANGLE+1.0471975*SND
1     CONTINUE
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      FUNCTION DIST(J)
C
C   DIST GENERATES THE DISTANCE TO THE NEXT RAIN CELL.  THE
C   DISTANCE IS RANDOMLY GENERATED.  IT CAN NOT EXCEED
C   THE MODE CELL RADIUS.
      COMMON /THPRE/ TYPE(8),ANOC(8),ADEP(8),ARAD(8)
      INTEGER TYPE
C
1     U=RANF(J)
      IF(U.GT.0.4) GOTO 2
      DIST=SQRT(25.8975*U)
      IF(DIST.GT.2*ARAD(J)) GOTO 1
      RETURN
2     DIST=.5*(16.092693-SQRT(155.38485*(1.0-U)))
      IF(DIST.GT.2*ARAD(J)) GOTO 1
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE CDEPTH(J)
C
C   CDEPTH GENERATES THE DEPTH OF RAINFALL AT THE CENTER OF
C   EACH CELL USING A NEGATIVE BINOMIAL DISTRIBUTION.
C
      COMMON /CELLS/ NOC,CX(20),CY(20),RAD(20),CELDEP(20)
      COMMON /THPRE/ TYPE(8),ANOC(8),ADEP(8),ARAD(8)
      INTEGER TYPE
C
      X=ADEP(J)
      DO 1 NC=1,NOC
1     CELDEP(NC)=-X*ALOG(RANF(J))
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      FUNCTION GCDEPTH(NG,NC)
C
C   GCDEPTH CALCULATES THE DEPTH OF RAINFALL AT A GAGE FROM
C   ONE CELL.
C
      COMMON /GAGES/ NGAGES,POINTS(100),GX(100),GY(100),
     *TH(100),INOUT(100)
      COMMON /CELLS/ NOC,CX(20),CY(20),RAD(20),CELDEP(20)
      INTEGER POINTS
C
      GCDEPTH=0.0
      X=GX(NG)-CX(NC)
      Y=GY(NG)-CY(NC)
      R=SQRT(X*X+Y*Y)
      IF(R.GE.RAD(NC)) RETURN
      IF(R.GT.0.9079328) GOTO 1
      GCDEPTH=CELDEP(NC)*(1.-(.11014027*R))
      RETURN
1     GCDEPTH=0.9*CELDEP(NC)*(1.-(ALOG(1.1014027*R)/ALOG(1.1
     *RAD(NC))))
      RETURN
      END
```

```
SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

      SUBROUTINE DFRONT(J)
C
C  DFRONT CALCULATES DEPTH OF RAINFALL FOR FRONTAL EVENTS
C  USING THE IMSL LIBRARY SUBROUTINE GGAMR.
C
      COMMON /FPRE/ DEPTH,FRLAM,FRKK
      COMMON /GAGES/ NGAGES,POINTS(100),GX(100),GY(100),
     *TH(100),INOUT(100)
      COMMON /PRECIP/ GDEPTHS(100)
      DIMENSION WK(2)
C
      CALL GGAMR (234.D0,FRKK,1,WK,DEPTH)
      DEPTH=DEPTH/FRLAM
      CALL FDEPTH
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE FDEPTH
C
C   FDEPTH DISTRIBUTES DEPTH OF RAINFALL RESULTING FROM
C   FRONTAL EVENTS UNIFORMLY OVER THE ENTIRE WATERSHED.
C
      COMMON /GAGES/ NGAGES,POINTS(100),GX(100),GY(100),
     *TH(100),INOUT(100)
      COMMON /FPRE/ DEPTH,FRLAM,FRKK
      COMMON /PRECIP/ GDEPTHS(100)
      INTEGER POINTS
C
      DO 1 NG=1,NGAGES
1     GDEPTHS(NG)=GDEPTHS(NG)+DEPTH
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE TDOR(I,L)
C
C   TDOR (TEMPORAL DISTRIBUTION OF RAINFALL)
C
C
C   THIS SUBROUTINE TEMPORALLY DISTRIBUTES RAINFALL THAT
C   OCCURS FOR EACH RAINFALL EVENT PRODUCED BY DROM.
C   IT PRINTS BEGINNING AND ENDING TIMES FOR EACH
C   RAINFALL EVENT.
C
      COMMON /MODEL/ DUM1,STORM(365),DUM2,MULTEV(365)
      COMMON /THTIME/ THM1,THM2(2),THM3(3),THSD(3),ELAM(2),
     *EK(2)
      COMMON /TEMP/ BTFRONT,ETFRONT,BTTHUND(3),ETTHUND(3)
      INTEGER STORM
C
C   THIS ROUTINE GENERATES BEGIN AND END TIMES FOR EACH EVENT
C   OCCURRENCE SIMULATED BY DROM
C
C   BRANCH TO THE TIME CALCULATION FOR A GIVEN STORM TYPE
C
      IF(I.EQ.ID) GOTO 2
      ID=I
      DO 1 LL=1,3
1     BTTHUND(LL)=ETTHUND(LL)=0.0
      T=BTFRONT=ETFRONT=0.0
2     IF(STORM(I).NE.4) GOTO 100
C
C   FRONTAL STORM - THE BEGIN AND END TIMES ARE UNIFORMLY
C   DISTRIBUTED OVER 24 HOURS.  END TIME MUST BE GREATER
C   THAN BEGIN TIME + 3 HOURS.
50    BTFRONT=RANF(I)*24.0
      IF(BTFRONT.GT.21.0) GOTO 50
      ETFRONT=BTFRONT+3.0+RANF(I)*(21.0-BTFRONT)
      RETURN
C
C   THUNDERSTORM - BEGIN TIME IS ASSIGNED BY FUNCTION
C   BTTH(T) WHERE T=END TIME OF LAST EVENT ON THIS DAY (OR
C   0.00 AT START).  THE RETURNED VALUE IS GUARANTEED
C   GREATER THAN T. END TIME IS ASSIGNED BY THE FUNCTION
C   ETTH(T) WHERE T=BEGIN TIME OF THE EVENT OBTAINED FROM
C   FUNCTION BTTH. THE RETURNED VALUE IS GUARANTEED GREATER
C   THAN T.
C
100   M=1
      IF(STORM(I).GT.4) M=2
      J=STORM(I)
      K=MULTEV(I)
101   T=BTTHUND(L)=BTTH(T,K,L)
      T=ETTHUND(L)=ETTH(T,M)
      IF(T.LT.24.0) GOTO 150
      IF(L.GT.1) GOTO 102
      T=0.0
      GOTO 101
102   T=BTTHUND(L-1)
      GOTO 101
C
C   STOP TIME CALCULATIONS IF THERE IS NO FRONTAL STORM
C
150   IF(STORM(I).LE.3) RETURN
C
```

```
SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

C  FRONTAL RAIN AND THUNDERSTORM - THE BEGIN TIME
C  OF THE FRONTAL IS TAKEN TO COINCIDE WITH THE FIRST
C  THUNDERSTORM EVENT.  THE END TIME IS COMPUTED
C  UNIFORMLY 3.0 HOURS AFTER THE BEGIN TIME AS ABOVE.
C
      BTFRONT=BTTHUND(1)
      IF(BTFRONT.GT.21.0) GOTO 100
      ETFRONT=BTFRONT+3.0+RANF(I)*(21.0-BTFRONT)
      RETURN
      END
```

```
SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

      FUNCTION BTTH(T,K,L)
C
C   FUNCTION BTTH USES THE IMSL LIBRARY FUNCTION GGNQF.
C   IT GENERATES A PSEUDO-RANDOM NORMAL DEVIATE WHICH IS
C   TRANSFORMED INTO A TIME USING THE MEAN AND STANDARD
C   DEVIATION OF ACTUAL DATA.
C
      COMMON /THTIME/ THM1,THM2(2),THM3(3),THSD(3),ELAM(2),
     *EK(2)
      COMMON /TEMP/ BTFRONT,ETFRONT,BTTHUND(3),ETTHUND(3)
      DIMENSION WS(6)
C
C   THIS ROUTINE GENERATES BEGIN AND END TIMES FOR
C   UP TO THREE THUNDRSTORMS.
      IF(K-2) 11,21,31
C
C   GENERATE BEGINNING TIME FOR ONE THUNDERSTORM PER DAY
C
11    RNN=GGNQF(234.D0)
      BTTH=RNN*THSD(K)+THM1
      IF(BTTH.LT.T+4.) GOTO 11
      RETURN
C
C   GENERATE BEGINNING TIME FOR TWO THUNDERSTORMS PER DAY
C
21    IF(L.GT.1) GOTO 22
      RNN=GGNQF(234.D0)
      BTTH=RNN*THSD(K)+THM2(L)
      IF(BTTH.LT.T+4.) GOTO 21
      RETURN
22    RNN=GGNQF(234.D0)
      BTTH=RNN*THSD(K)+THM2(L)
      IF(BTTH.LT.T+4.) GOTO 22
      RETURN
C
C   GENERATE BEGINNING TIMES FOR THREE THUNDERSTORMS PER DAY
C
31    IF(L.GT.1) GOTO 32
      RNN=GGNQF(234.D0)
      BTTH=RNN*THSD(K)+THM3(L)
      IF(BTTH.LT.T+3.0) GOTO 31
      RETURN
32    IF(L.GT.2) GOTO 33
      RNN=GGNQF(234.D0)
      BTTH=RNN*THSD(K)+THM3(L)
      IF(BTTH.LT.T+3.0) GOTO 32
      RETURN
33    RNN=GGNQF(234.D0)
      BTTH=RNN*THSD(K)+THM3(L)
      IF(BTTH.LT.T+3.0) GOTO 33
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATCOR)

```
      FUNCTION ETTH(T,M)
C
C   FUNCTION ETTH USES THE IMSL LIBRARY SUBROUTINE GGAMR.
C   IT GENERATES A PSEUDO-RANDOM GAMMA DEVIATE BASED ON THE
C   SHAPE (K) PARAMETER AND THE SCALE (LAMBDA) PARAMETER OF
C   ACTUAL DURATION DATA.
C
C   LAMBDA= MEAN/VARIANCE
C   K=MEAN*MEAN/VARIANCE
C
      COMMON /THTIME/ THM1,THM2(2),THM3(3),THSD(3),ELAM(2),
     *EK(2)
      COMMON /TEMP/ BTFRONT,ETFRONT,BTTHUND(3),ETTHUND(3)
      DIMENSION WS(6)
C
1     CALL GGAMR (234.D0,EK(M),1,WS,THDUR)
      THDUR=THDUR/ELAM(M)
      IF(THDUR.LT.0.08333.OR.THDUR.GT.1.000) GOTO 1
      ETTH=T+THDUR
      RETURN
      END
```

SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL (SATDOR)

```
      SUBROUTINE PRINTER (I,J,L)
C
      COMMON /FPRE/ DEPTH,FRLAM,FRKK
      COMMON /PRECIP/ GDEPTHS(100)
      COMMON /GAGES/ NGAGES,POINTS(100),GX(100),GY(100),
     *TH(100),INOUT(100)
      COMMON /STAT/ RANE(366,5),NN,DGDEP(5),GAGECHK(5)
      COMMON /CELLS/ NOC,CX(20),CY(20),RAD(20),CELDEP(20)
      COMMON /TEMP/ BTFRONT,ETFRONT,BTTHUND(3),ETTHUND(3)
      INTEGER GAGECHK,POINTS
      DATA ID/0/
C
      WRITE(2,800) I,L,NOC,DEPTH
      IF(NOC.GT.0) WRITE(2,801)(N,CX(N),CY(N),RAD(N),
      CELDEP(N),N=1,NOC)
      WRITE(2,802) (POINTS(N),GX(N),GY(N),GDEPTHS(N),
     *TH(N)*GDEPTHS(N),INOUT(N),N=1,NGAGES)
      WRITE(2,803) L,L,BTFRONT,ETFRONT,BTTHUND(L),ETTHUND(L)
      WRITE(4,901) I,J,L,DEPTH,(POINTS(N),GDEPTHS(N),N=1,
      NGAGES)
      WRITE(4,902) BTFRONT,ETFRONT,BTTHUND(L),ETTHUND(L)
800   FORMAT(" ",1(/)," DAY NUMBER = ",I3,5X,"NO. OF "
     *"THUNDERSTORMS = ",I1,5X,"NUMBER OF CELLS = ",I1,
     *5X,"FRONTAL DEPTH = ",F5.3,/)
801   FORMAT(4X,"CELL NO. X-ORDINATE Y-ORDINATE    RADIUS  "
     *,"  DEPTH",11X,"CELL NO. X-ORDINATE Y-ORDINATE   ",
     *"RADIUS      DEPTH",/,(" ",5X,I2,6X,F7.3,4X,F7.3,5X,
     *F6.3,4X,F6.3,14X,I2,6X,F7.3,4X,F7.3,5X,F6.3,4X,F6.3))
     *5X,F6.3,4X,F6.3))
802   FORMAT(1H0,3(3X,"NO.    X      Y    DEPTH WT.DEPTH ",
     *"INOUT"),//,3(" ",2X,I3,2X,F5.2,2X,F5.2,2X,F5.3,3X,
     *F5.3,4X,I1,1X))
803   FORMAT(1H0, 5X,"BTFRONT",6X,"ETFRONT",7X,"BTTHUND",I1,
     *7X,"ETTHUND",I1,//,(7X,F5.2,8X,F5.2,9X,F5.2,9X,F5.2))
900   FORMAT(I3)
901   FORMAT(I3,1X,I1,1X,I1,1X,F7.4,/,10(I3,F6.4))
902   FORMAT(4(F5.2,2X))
      RETURN
      END
```

APPENDIX B

LISTING OF VARIABLES IN SATDOR

LIST OF VARIABLES USED BY SATODR

```
ADEP     - AVERAGE RAINFALL DEPTH AT CENTER OF STORM CELLS
ANGLE    - ANGLE (RADIANS) FOR DIRECTION TO NEXT STORM CELL
ANOC     - AVERAGE NUMBER OF CELLS IN A THUNDERSTORM
ARAD     - AVERAGE RADIUS OF STORM CELLS
ARAF     - AREAL ADJUSTMENT FACTOR
AREA     - AREA OF WATERSHED
AREAB    - AREA OF WATERSHED WITH BUFFER ZONES INCLUDED
BEGIN    - FIRST DAY OF SEASON TO BE SIMULATED
BTFRONT  - BEGINNING TIME FOR FRONTAL EVENTS
BTTHUND  - BEGINNING TIME FOR THUNDERSTORM EVENTS
CELDEP   - DEPTH OF RAINFALL AT CENTER OF STORM CELL
CX       - X COORDINATE OF CENTER OF STORM CELL
CY       - Y COORDINATE OF CENTER OF STORM CELL
DELX     - LENGTH OF WATERSHED AND BUFFER ZONE IN THE
           X DIRECTION
DELY     - LENGTH OF WATERSHED AND BUFFER ZONE IN THE
           Y DIRECTION
DEPTH    - DEPTH OF FRONTAL EVENT
DGDEP    - DAILY DEPTH OF RAINFALL AT A PARTICULAR GAGE
EK       - K (SHAPE PARAMETER) FOR GAMMA DISTRIBUTION FOR
           ENDING TIME OF THUNDERSTORM
ELAM     - LAMBDA (SCALE PARAMETER) FOR GAMMA DISTRIBUTION
           FOR ENDING TIME OF THUNDERSTORM
EMEAN    - MEAN FOR DURATIONS FOR THUNDERSTORM EVENTS
END      - LAST DAY OF SEASON TO BE SIMULATED
ETFRONT  - END TIME FOR FRONTAL EVENTS
ETTHUND  - END TIME FOR THUNDERSTORM EVENTS
EVAR     - VARIANCE FOR DURATIONS FOR THUNDERSTORMS
FRKK     - K (SHAPE PARAMETER) FOR GAMMA DISTRIBUTION FOR
           RAINFALL DEPTH OF FRONTAL EVENT
FRLAM    - LAMBDA (SCALE PARAMETER) FOR GAMMA DISTRIBUTION
           FOR RAINFALL DEPTH OF FRONTAL EVENT
FRPER    - PERSISTENCE PARAMETER FOR FRONTAL EVENTS
FRMEAN   - MEAN FOR DEPTH OF FRONTAL EVENT
FRVAR    - VARIANCE FOR DEPTH OF FRONTAL EVENT
GAGECHK  - GAGE LOCATIONS WHERE SEASONAL TOTALS ARE COMPUTED
GAGENOS  - NUMBER OF THE RAINFALL GAGE
GCDEPTH  - RAINFALL DEPTH AT GAGE FOR ONE STORM CELL
GDEPTH   - DEPTH OF RAINFALL AT GAGE FOR ONE STORM
GX       - X COORDINATE OF GAGE LOCATION
GY       - Y COORDINATE OF GAGE LOCATION
HIGHT    - ELEVATION OF WATERSHED TO BE MODELED
INOUT    - GAGE LOCATION, (INOUT>0 =ON THE WATERSHED,
           INOUT=0 =OFF THE WATERSHED)
KOUNT    - COUNTER USED TO SORT OUT SIGNIFICANT RAINFALL
           EVENTS
LAT      - LATITUDE OF WATERSHED TO BE MODELED
LONG     - LONGITUDE OF WATERSHED TO BE MODELED
MULTEV   - NUMBER OF RAINFALL EVENTS OCCURRING ON ONE DAY
NGAGES   - NUMBER OF GAGES USED TO DEFINE WATERSHED
           AND USED IN CALCULATIONS
NOC      - NUMBER OF CELLS IN ONE THUNDERSTORM
NYEARS   - NUMBER OF YEARS TO BE SIMULATED
PFIRST   - PROBABILITY OF OCCURRENCE OF RAINFALL EVENT
PMULTI   - PROBABILITY OF OCCURRENCE OF MULTIPLE
           THUNDERSTORM EVENTS
POINTS   - GAGE LOCATION NUMBERS
PRAF     - PROBABILITY ADJUSTMENT FACTOR
PROB2    - PROBABILITY OF TWO THUNDERSTORM PER DAY
PROB3    - PROBABILITY OF THREE THUNDERSTORMS PER DAY
PSE      - PROBABILITY DISTRIBUTION FOR SE THUNDERSTORMS
```

LIST OF VARIABLES USED BY SATDOR

R - DISTANCE FROM CENTER OF STORM CELL TO GAGE
RAD - RADIUS OF THE STORM CELL
RANE - DAILY RAINFALL RECORD (TOTAL AMOUNT FOR DAY) NUMBERS
REGION - REGION OF ARIZONA AND NEW MEXICO TO BE MODELED
STORM - TYPE OF STORM SIMULATED
SWPER - PERSISTENCE PARAMETER FOR SW RAINFALL
SYMBOL - OUTPUT SYMBOLS USED FOR RAINFALL TYPES
TH - THIESSEN WEIGHT ASSOCIATED WITH THE GAGE
THDUR - DURATION OF THUNDERSTORM EVENT
THM1 - MEAN BEGINNING TIME FOR ONE THUNDERSTORM
THM2 - MEAN BEGINNING TIMES FOR TWO THUNDERSTORMS
THM3 - MEAN BEGINNING TIME FOR THREE THUNDERSTORMS
THSD - STD. DEVIATION FOR BEGINNING TIME OF THUNDERSTORM
TYPE - COMBINATION OF MOISTURE SOURCES FOR EACH RAINFALL EVENT
XL - X COORDINATE, LOWER LIMIT OF OCCURRENCE MODEL
XU - X COORDINATE, UPPER LIMIT OF OCCURRENCE MODEL
YL - Y COORDINATE, LOWER LIMIT OF OCCURRENCE MODEL
YU - Y COORDINATE, UPPER LIMIT OF OCCURRENCE MODEL

APPENDIX C

USER'S GUIDE FOR SATDOR

USER'S GUIDE FOR SATDOR

PROGRAM SATDOR WAS DESIGNED TO BE USED AS A SERIES OF COMPONENTS. IT CAN BE SET UP IN FOUR CONFIGURATIONS TO SIMULATE DIFFERENT TYPES OF RESULTS.

1. DAILY RAINFALL OCCURRENCE RECORDS
2. DAILY RAINFALL OCCURRENCE RECORDS WITH SPATIAL DISTRIBUTION OF RAINFALL
3. DAILY RAINFALL OCCURRENCE RECORDS WITH TEMPORAL DISTRIBUTION OF RAINFALL
4. DAILY RAINFALL OCCURRENCE RECORDS WITH SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL

SATDOR CONSISTS OF 7 MAIN SUBROUTINES. THE SUBROUTINES WERE DESIGNED TO BE AS NEARLY INDEPENDENT OF EACH OTHER AS WAS PRACTICAL. VARIABLES REQUIRED FOR PARTICULAR COMPONENTS ARE STORED IN THE SAME COMMON BLOCKS. CALCULATIONS FOR PARTICULAR COMPONENTS ARE FOUND IN APPLICABLE SUBROUTINES ONLY. INSTRUCTIONS FOR PRINTING OUTPUT ARE CONTAINED IN VARIOUS PROGRAM SEGMENTS.

THREE SUBROUTINES ARE REQUIRED FOR OPERATION OF THE PROGRAM.

1. WSHED - DEFINES WATERSHED BOUNDARIES AND AREAL RELATIONSHIPS.
2. PDF - PROVIDES PARAMETERS AND PROBABILITY DISTRIBUTION FOR RAINFALL OCCURRENCE MODEL
3. DROM - GENERATES DAILY RAINFALL OCCURRENCE RECORD

TO PROVIDE THE SPATIAL DISTRIBUTION OF RAINFALL, TWO ADDITIONAL SUBROUTINES ARE NECESSARY.

4. SPAR - READS IN SPATIAL DISTRIBUTION PARAMETERS
5. SDOR - GENERATES SPATIAL DISTRIBUTION PATTERNS FOR GIVEN RAINFALL EVENTS.

TO PROVIDE THE TEMPORAL DISTRIBUTION OF RAINFALL, TWO ADDITIONAL SUBROUTINES ARE NECESSARY.

6. TPAR - READS IN TEMPORAL DISTRIBUTION PARAMETERS
7. TDOR - GENERATES BEGINNING AND END TIMES, AND DURATIONS FOR GIVEN RAINFALL EVENTS.

PROGRAM SATDOR GENERATES OUTPUT FROM THREE SUBPROGRAMS.

SUBROUTINE DROM PRINTS A SEASONAL SUMMARY OF THE RAINFALL OCCURRENCES GENERATED BY DROM.

USER'S GUIDE FOR SATDOR

SUBROUTINE PRINTER PRINTS AN EVENT BY EVENT SUMMARY OF THE SPATIAL AND TEMPORAL DISTRIBUTION OF RAINFALL ON DAYS THAT RAINFALL OCCURRENCE IS SIMULATED AND WRITES THE SPATIAL AND TEMPORAL DISTRIBUTION OF MAJOR EVENTS TO A SCRATCH FILE (TAPE4) TO BE USED AS INPUT TO DRIVE A DETERMINISTIC WATERSHED MODEL.

THE MAIN PROGRAM PRINTS AN ANNUAL SUMMARY OF DAILY RAINFALL AMOUNTS AND WRITES THE DAILY AMOUNTS AND EVENT TYPES TO TWO SCRATCH FILES (TAPE3 AND TAPE5) TO BE USED FOR STATISTICAL ANALYSIS OF SIMULATION RESULTS. RAINFALL AMOUNTS AND RAINFALL TYPES TO TWO SCRATCH FILES TO BE USED FOR STATISTICAL ANALYSIS OF THE SIMULATION RESULTS.

THE FOLLOWING ARE DESCRIPTIONS OF SUBROUTINES AND FORMATS USED TO INPUT DATA FOR PROGRAM SATDOR:

SUBROUTINE WSHED

THIS SUBROUTINE READS IN THE LOCATION OF RAIN GAGES ON OR OFF THE WATERSHED. RAIN GAGES MUST BE LOCATED ON THE CORNER OF THE WATERSHED TO DEFINE THE TOTAL AREA FOR THE OCCURRENCE MODEL.

THE DATA FOR THIS SUBROUTINE IS READ IN BY THIS SUBROUTINE. INPUT DATA SHOULD RESIDE ON TAPE1 IN CARD IMAGE FORMAT. NO ERROR CHECKING OF THE DATA IS PERFORMED.

```
CARD 1: I10,F10.3,5I10
        NN      - NUMBER OF GAGES TO BE CHECKED
        ARAF    - AREAL ADJUSTMENT FACTOR
        GAGECHK - LOCATION NUMBER TO BE CHECKED

CARD N: 2I10,3F10.3 (UP TO 100 GAGE LOCATIONS)
        POINTS  - NUMBER OF GAGE
        INOUT   - (1-9) - ON THE WATERSHED
                  (0) - OFF THE WATERSHED
        GX      - X COORDINATE OF LOCATION OF GAGE
        GY      - Y COORDINATE OF LOCATION OF GAGE
        TH      - THIESSEN WEIGHT OF GAGE
```

SUBROUTINE PDF

THIS SUBROUTINE READS IN PARAMETERS FOR THE RAINFALL OCCURRENCE MODEL, SUBROUTINE DROM.

THE DATA FOR THIS SUBROUTINE IS READ IN BY THIS SUBROUTINE. INPUT DATA SHOULD RESIDE ON TAPE1 IN CARD IMAGE FORMAT. NO ERROR CHECKING OF THE DATA IS PERFORMED.

```
CARD 1: 3I5
        NYEAR   - NUMBER OF YEARS TO BE SIMULATED
        BEGIN   - FIRST DAY NUMBER OF SEASON TO BE SIMULATED
        END     - LAST DAY NUMBER OF SEASON TO BE SIMULATED

CARD 2: I5,3F10.3
        REGION  - REGION CONTAINING THE WATERSHED
        LAT     - LATITUDE OF THE WATERSHED
```

```
        LONG     - LONGITUDE OF THE WATERSHED
        HIGHT    - ELEVATION OF THE WATERSHED TO BE MODELED

CARD 3: 5F10.8
        PROB2    - PROBABILITY OF TWO THUNDERSTORMS PER DAY
        PROB3    - PROBABILITY OF THREE THUNDERSTORMS PER DAY
        SWPER    - PERSISTENCE OF SW MOISTURE
        FRPER    - PERSISTENCE OF FRONTAL MOISTURE
        PRAF     - PROBABILITY ADJUSTMENT FACTOR

CARDS 4-18: 25I3(TWO DECIMALS ASSUMED,365 VALUES)
        PSE      - SE DAILY PROBABILITIES AT THE BASE STATION
                   FOR REGION 1

CARDS 19-33: 25I3(TWO DECIMALS ASSUMED,365 VALUES)
        PSE      - SE DAILY PROBABILITIES AT THE BASE STATION
                   FOR REGION 2

CARDS 34-48: 25I3(TWO DECIMALS ASSUMED,365 VALUES)
        PSE      - SE DAILY PROBABILITIES AT THE BASE STATION
                   FOR REGION 3


     SUBROUTINE SPAR

THIS SUBROUTINE READS ON PARAMETERS FOR THE SPATIAL
DISTRIBUTION OF RAINFALL.

THE DATA FOR THIS SUBROUTINE IS READ IN BY THIS SUBROUTINE.
INPUT DATA SHOULD RESIDE ON TAPE1 IN CARD IMAGE FORMAT.
NO ERROR CHECKING OF THE DATA IS PERFORMED.

CARDS 1-7: I1,9X,3F10.5
         TYPE     - RAINFALL EVENT TYPE
         ANOC     - AVERAGE NUMBER OF CELLS IN A THUNDERSTORM
         ADEP     - AVERAGE RAINFALL DEPTH AT THE CENTER OF
                    STORM CELLS
         ARAD     - AVERAGE RADIUS OF STORM CELLS

CARD 8: 2F10.7
         FRMEAN   - MEAN DEPTH FOR FRONTAL EVENT
         FRVAR    - VARIANCE OF DEPTH FOR FRONTAL EVENT


     SUBROUTINE TPAR

THIS SUBROUTINE READS IN PARAMETERS FOR THE TEMPORAL
DISTRIBUTION OF RAINFALL.

THE DATA FOR THIS SUBROUTINE IS READ IN BY THIS SUBROUTINE.
INPUT DATA SHOULD RESIDE ON TAPE1 IN CARD IMAGE FORMAT.
NO ERROR CHECKING OF THE DATA IS PERFORMED.

CARD 1: 9F7.5
         THM      - MEAN BEGINNING TIME FOR THUNDERSTORM(S)
         THSD     - STANDARD DEVIATION FOR BEGINNING TIME OF
                    THUNDERSTORM(S)
CARD 2: 2F10.7
         EMEAN    - MEAN DURATION FOR THUNDERSTORM EVENT(S)
         EVAR     - VARIANCE OF DURATION FOR THUNDERSTORM EVE
```

INPUT DATA FOR 100 YEAR SIMULATION AT UPPER W-18 WATERSHED

```
         5     3.400        41        06        35          15
        26
        41        15     03.00     09.00    1.0
        06        01      2.00     16.00    1.00
        35        14     04.00      2.00    1.0
        15        05     04.00     12.00    1.00
        26        10      2.00     06.00    1.0
        07        15      4.00     16.00    1.00
        10        02     02.00     14.00    1.00
        11        03     04.00     14.00    1.00
        14        04      2.00     12.00    1.00
        18        06     02.00     10.00    1.00
        19        07      4.00     10.00    1.00
        22        08      2.00      8.00    1.0
        23        09      4.00     08.0     1.
        27        11      4.00     06.00    1.0
        30        12      2.00     04.00    1.00
        31        13     04.00     04.00    1.00
        34        15     02.00      2.00    1.00
         1         0      0.00     18.00    1.00
         2         0      2.00     18.00    1.0
         3         0      4.00     18.00    1.0
         4         0      6.00     18.00    1.0
         5         0      0.00     16.00    1.00
         8         0      6.00     16.00    1.
         9         0      0.0      14.0     1.
        12         0      6.00     14.00    1.0
        13         0      0.00     12.00    1.00
        16         0      6.00     12.00    1.00
        17         0      0.00     10.00    1.00
        20         0      6.00     10.00    1.00
        21         0      0.00      8.00    1.00
```

```
INPUT DATA FOR 100 YEAR SIMULATION AT UPPER W-1B WATERSHED
               24             0        6.00      08.00       1.00
               25             0        0.00      06.00       1.00
               28             0       06.00      06.00       1.0
               29             0       00.00      04.00       1.0
               32             0       06.00      04.00       1.00
               33             0       00.00       2.00       1.0
               36             0       06.00      02.0        1.
               37             0       00.00      00.00       1.
               38             0       02.0        0.0        1.
               39             0       04.0        0.00       1.0
               40             0       06.00      00.00       1.0
```

```
INPUT DATA FOR 100 YEAR SIMULATION AT UPPER W-18 WATERSHED
  100  121  304
   03       32.14     110.77   0902.00
     0.200      0.040      0.750      0.750      0.840
 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
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 01 01 01 01 01
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 03 03 03 03 03
 03 04 04 04 05 05 05 05 05 06 06 07 07 08 08 09 09 10 10 11
 12 12 12 13 13
 13 14 14 14 15 15 15 15 15 16 16 16 17 16 16 16 15 15 15 15
 15 14 14 14 13
 13 13 13 12 12 12 12 12 12 12 12 13 13 14 14 14 14 15 15 15
 15 16 16 16 16
 16 17 17 17 18 18 18 18 19 19 19 19 19 20 20 20 20 20 20 20
 20 20 20 20 20
 20 20 20 20 19 19 19 18 18 17 17 16 16 15 15 14 14 13 12 11
 10 09 08 07 06
 05 04 03 03 02 02 01 01 01 01 01 01 01 00 00 00 00 00 00 00
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 02 02 02 02 02
 02 03 03 04 04 04 05 05 05 06 06 06 07 07 07 07 08 08 08 09
 09 10 10 11 11
 12 12 13 13 14 14 15 15 16 16 17 17 18 18 19 19 20 20 21 21
 22 22 23 23 24
 24 25 25 26 26 26 27 27 27 27 27 28 28 28 28 28 28 28 28 27
 27 27 26 26 25
 25 24 24 23 22 21 21 20 20 20 20 20 20 20 21 21 22 22 22 22
 23 23 23 23 22
 22 22 21 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05
 04 03 02 02 01
 01 01 01 01 01 01 01 01 01 01 01 01 01 00 00 00 00 00 00 00
 00 00 00 00 00
 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 00 00 00 00 00
```

```
INPUT DATA FOR 100 YEAR SIMULATION AT UPPER W-1B WATERSHED
 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 00 00 00 00 00
 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00

 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
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 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 01 01 01 01 01
 01 01 01 01 01
 01 01 02 02 02 02 02 03 03 03 03 04 04 04 05 05 06 06 07 07
 08 08 09 10 11
 12 13 14 15 16 17 18 19 20 22 23 25 27 29 31 33 35 37 39 41
 43 44 45 46 47
 48 48 49 49 50 50 50 50 50 50 49 49 49 48 48 47 47 46 46 45
 45 44 44 43 42
 41 40 39 38 37 36 35 35 34 34 33 33 32 32 31 31 30 30 29 29
 28 27 27 26 26
 25 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07
 06 05 04 03 03
 02 02 02 02 01 01 01 01 01 01 01 01 01 00 00 00 00 00 00 00
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 00 00 00 00 00
 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0          0         0         0
1        04.5       1.0       2.5
2        04.5       1.0       2.5
3        04.5       1.0       2.5
4        0.00       0.0       0.00
5        05.5       1.5       3.0
6        05.5       1.5       3.0
7        05.5       1.5       3.00
     0.30   0.0900
17.0   2.0    15.0   21.0   1.50   13.0   16.0   19.0   1.0
0.250     0.0625   0.35      0.1225
```

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