RADAR-RAINFALL DATA FOR THE GREAT FLOOD OF 1993

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Introduction

For much of 1993, the Midwest was pounded by a relentless series of storms that spawned one of America's worst natural disasters. Long-standing rainfall records were toppled and river levels were pushed to record heights in seven states. Some reported river levels remained above flood stage for 200 days. A few stations saw sustained river levels above previously record flood crests for as long as 30 days. Fifty flood deaths occurred, hundreds of major river levees failed, and damages approached $15 billion (NWS Central Region, 1994).

The nation's economy was impacted as the great flood disrupted transportation systems throughout the Midwest. Barge traffic along the Mississippi and Missouri rivers stalled for nearly two months due to high water and treacherous currents. Bridges were out, airports were flooded, major interstate highways were closed, and the trains stopped running.

The region is still suffering. Many homes were destroyed, some never to be rebuilt. Damaged farmlands may take years to recover, if ever. Major rivers reclaimed land that for decades had been denied them by a network of levees and flood control works. So great was the flooding that the foundations of flood control in this country were shaken. Federal and state agencies are revisiting decades-old flood control polices and, in some cases, formulating new approaches (Denning, 1994).

As with any natural disaster, the Great Flood of 1993 is being studied in detail to determine exactly what happened and why. This paper presents a new data set that may help event analysis. A data set derived from a new approach to radar-based rainfall estimates is presented. It includes 15-minute rainfall accumulations in 0.01" increments with 2 km x 2 km resolution for the period April 1 to August 31, 1993, for the entire upper Midwest region. A comparative data set comprised of traditional observed rain gauge measurements is also presented and contrasted with the radar-based rainfall estimates.

Traditional Rainfall Measurement

Measurements of rain are usually taken using some sort of mechanical rain gauge. Rain gauges used in hydrometeorological applications are typically cylindrical devices that sample rain falling through an orifice 8-12 inches in diameter. Rainfall is commonly measured in a variety of ways. Simple measuring sticks, weighing the accumulated sample, and tipping buckets are typical techniques used to estimate the accumulated depth of rainfall.

The purpose of a rainfall measurement for most hydrometeorological applications is to use the measurement to estimate the amount of rainfall over a much larger area. Often a network of rain gauges is used to estimate the average rainfall over a watershed. The average rainfall over an area is a measure of the total volume of rain entering the area. The total volume of rain is the key parameter of interest.

Rain gauges generally provide adequate estimates of rain falling through the gauge orifice. The difficulty lies in the translation of point estimates to areal estimates. It is not uncommon to use an 8" rain gauge with an orifice that covers just one eighty millionth of a square mile to infer the volumetric influx over 50 or 100 square miles. Hydrologists are routinely forced to accept volumetric inflow estimates using samples on a scale of "parts per billion." Without additional information, it is difficult to consistently infer accurate areal rainfall estimates from a sparse network of gauges given the variety of meteorological conditions that can occur.

Radar-Based Rainfall Measurement

Radar has long been a logical alternative to rain gauges as an estimator of areal rainfall (Atlas, 1990). Radar signals reflected from rain in the atmosphere provide a continuum of information related to areal rainfall. By integrating radar-determined rainfall intensities over time, rainfall accumulations can be approximated throughout the area of radar coverage. Theoretically, radar can provide measurements of rainfall that are superior to those from rain gauges since radar offers continuous coverage rather than "hit or miss" point estimates.

Unfortunately, historical efforts to estimate rainfall amounts using radar have been plagued by several problems. Ground clutter, anomalous signal propagation, and curvature of the earth's surface all create serious estimation problems. New technologies and approaches to radar signal interpretation are helping improve radar-rainfall estimation. For example, the National Weather Service is currently installing a new network of Doppler radars (WSR-88D/NEXRAD). The NEXRAD radars are more sensitive, have improved vertical discrimination, and higher resolution than previous radars. The NEXRAD network includes more complete coverage in the eastern United States and extends coverage in the mountainous West. All of these features are expected to help improve radar-rainfall estimation.

Implications for Hydrologic Applications

Perhaps no other hydrometeorological parameter imparts such a continuing high level impact on the nation's economy as does water. Hydroelectric power generation, agriculture, transportation, recreation, manufacturing of all types, and the operation of our homes are all inexorably linked to the reliable delivery of water via rainfall. The accurate determination of the volume of falling water affects decisions whose economic impacts run in the billions. Damages from flooding average $5 billion each year. The drought of 1980 cost the United States more than $20 billion. NEXRAD benefits to the nation's water resources are expected to far exceed the cost of the entire NEXRAD program.

A New Approach to Radar Imaging

Since 1988, WSI Corporation has been assimilating reflectivity data from conventional and NEXRAD (as available) radar sites throughout the country and combining these images into one mosaic of radar reflectivity. The mosaic presents radar images on a base map covering more than 6.5 million square miles at a resolution of 1.5 square miles (2 km x 2 km). These high resolution images are updated every 15 minutes.

Each pixel represents the average rainfall intensity over a 1.5 square mile area at the time of observation and is a composite representation derived from several radar sites. By using data from multiple radar sites to derive rainfall information, more complete coverage is possible than with single site images. Using proprietary three-stage false echo suppression/quality assurance processing, the mosaiced images avoid ground clutter, anomalous propagation, and other non-precipitation artifacts. With several radars viewing the same storm from different angles and distances, a more accurate storm structure emerges.

Rainfall rates associated with various levels of radar reflectivity values are commonly defined by the following relationship:

$$Z = aR^b$$

where Z is the radar reflectivity (mm^6/m^3) and R is the rainfall intensity (mm/hr). This equation is also commonly referred to as the "Z/R" relationship. The parameters "a" and "b" can vary considerably. Specific values of "a" and "b" depend on weather conditions, precipitation type, etc. Optimum values of "a" and "b" can change greatly in both space and time, even on a local scale.

WSI developed a new approach to the interpretation of reflectivity data that overcomes the problems associated with widely varying parameters in the Z/R relationship. WSI has developed an automated empirical weather condition-based approach to process data from both conventional radars and the new NEXRAD sites. A self-adjusting algorithm was developed to automatically select the most appropriate rainfall values for different weather conditions for each pixel in the image. Six- and 24-hour rain gauge reports from NWS 1st-order stations are used to calibrate and fine-tune rainfall estimates.

Rainfall accumulations are determined by integrating the derived rainfall intensities over time. Every 15 minutes the mosaiced reflectivity values, along with observations and computer model forecasts, are input into the empirical model, which generates accumulated rainfall for each 2 km x 2 km pixel in 0.01" increments. The resulting data set represents rainfall accumulations for more than 6.5 million pixels. WSI markets this data set commercially under the trade name PRECIP.™

Data for the Great Flood of 1993

In February 1993, for reasons not associated with the developing flood situation in the Midwest, WSI began archiving the radar-rainfall data set. As the circumstances developed, it became clear that this data set represented an intriguing opportunity to evaluate the region-wide evolution of the Great Flood almost minute by minute with great spatial detail. The data set for the 1993 flood includes rainfall accumulations for each 1.5 square mile pixel every 15 minutes. This is an unprecedented amount of rainfall information to support analysis of an unprecedented flood event.

Detailed analysis of the data has just begun. The sheer volume of data presents handling problems since the complete data set requires approximately several gigabytes of storage. For the purposes of this paper, monthly images of PRECIP for April through August 1993 were analyzed. These images were accessible "on-line" at WSI and reduced the data handling requirements.

Rainfall data for standard surface rain gauges were obtained for the 5-month period for the state of Iowa. These data, obtained from reports published by the National Weather Service's National Climate Data Center, were derived from 66 recording rain gauges located at National Weather Service, Federal Aviation Administration, and cooperative observer weather stations. Hourly data for each gauge were aggregated into monthly values. The monthly data were evaluated for each of the 66 stations. For one reason or another, monthly records were not complete at some stations due to mechanical failures, fouled gauges, etc. Only complete records were used in this analysis. On a monthly basis, the number of complete useable records decreased steadily from a high of 55/66 (86%) in April to a low of 46/66 (70%) in July. Just 28/66 (42%) of the stations maintained complete records during the full 5-month period.

To compare the areal radar-based rainfall estimates (PRECIP) with point rain gauge estimates, monthly PRECIP values for the 2 km x 2 km pixels containing the latitude-longitude coordinates of the rain gauges were used.

Results

Gauge-PRECIP data pairs were plotted on scatter diagrams as shown in Figure 1. Each data pair represents a monthly rain gauge total and a monthly PRECIP total for the pixel containing the rain gauge. Monthly averages were calculated for available rain gauge totals each month and their corresponding PRECIP totals. The monthly averages are shown in Table 1.

Table 1. Monthly rainfall averages in inches.

	April	May	June	July	August
Rain Gauge	3.33	5.40	7.83	10.67	7.14
PRECIP	3.75	6.58	9.45	11.60	8.54
Data Points	57	52	49	46	48

On average, monthly totals for PRECIP were 12-22% higher than observed rain gauge totals. For the entire 5-month period, monthly PRECIP was about 16% higher than the average rain gauge value. The scatter diagrams in Figure 1 show positive correlation but also considerable dispersion. PRECIP produced consistently higher amounts each month. April was the only month with incidences (4) of major underestimation by PRECIP. Closer examination revealed that all four were located in northwest Iowa. This section of Iowa is primarily covered by older network radars located in Huron, South Dakota, Des Moines, Iowa, and Minneapolis, Minnesota. A NEXRAD radar has recently been installed at Sioux Falls, South Dakota, which should improve radar-rainfall estimation in northwestern Iowa.

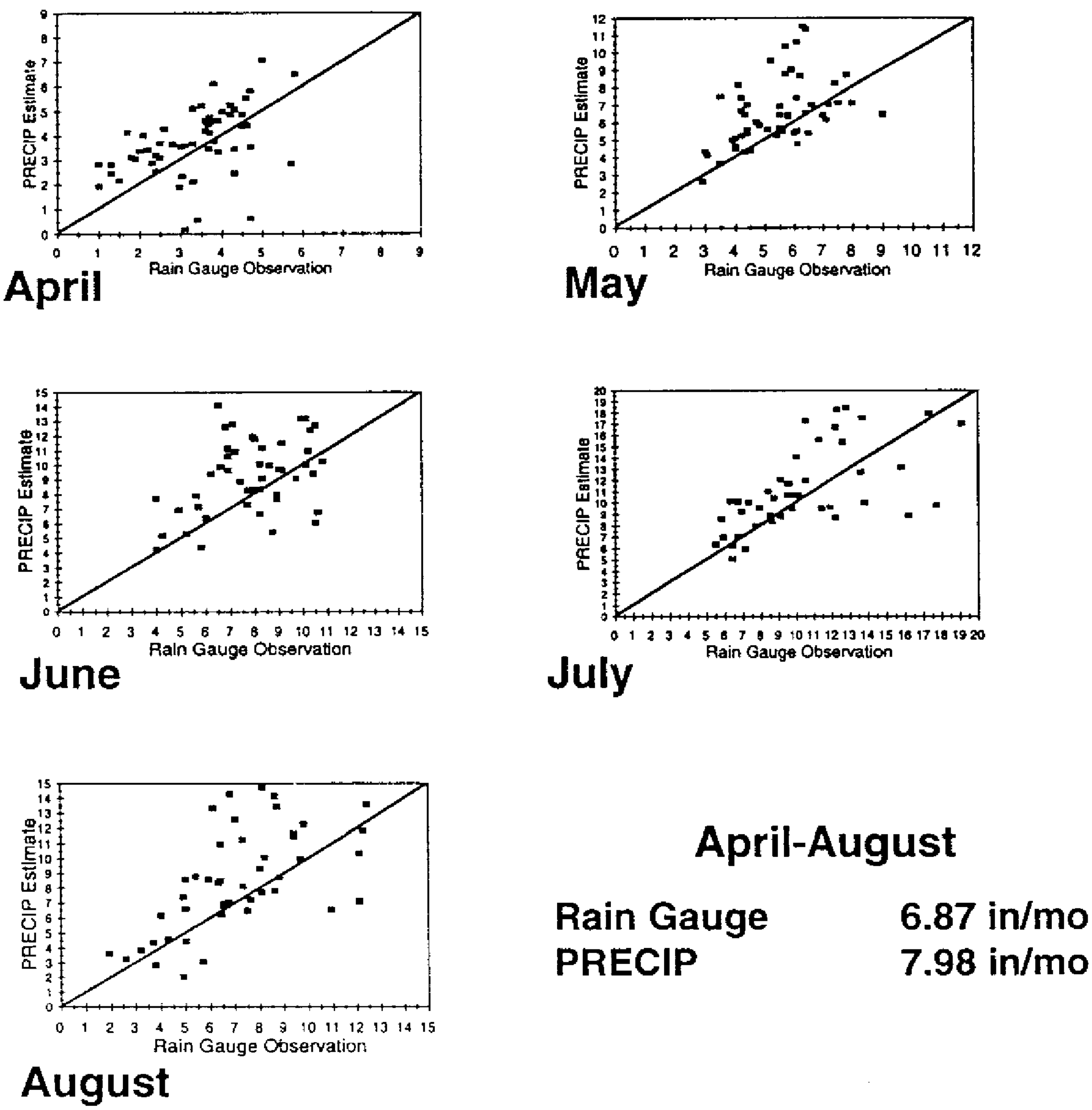

Figure 1. April-August PRECIP vs. rain gauge scatter diagrams.

Analysis

Overall, the performance of PRECIP estimates of rainfall are quite promising. For the entire April to August period, PRECIP averaged about 16% higher than rain gauge totals. Considering that long-term rain gauge measurements have been shown to underestimate actual rainfall by 5-15% (Groisman and Legates, 1994), the PRECIP averages look even better. There is still considerable variation in the data as shown by the dispersion indicated by the scatter diagrams. In general, some variation is expected since PRECIP estimates are areal and gauge readings are point values. Both measurements can be "correct" yet be significantly different. More likely, however, variability is introduced by anomalies remaining in the radar data set, uncertainties in the radar-rainfall estimation algorithms, inconsistencies in coverage by the radar network, individual storm conditions, inconsistencies created by merging NEXRAD with conventional radar data, etc.

Conclusions

On average, the radar-based rainfall estimation algorithms for generating PRECIP data performed well. Further experience and research will determine how consistently PRECIP performs on a storm-by-storm basis for individual locations and defined areas, such as watersheds.

Consistency will be difficult to determine in the short term as the conventional radar network is phased out in favor of NEXRAD. While NEXRAD holds great promise to improve radar-rainfall estimation, the "learning curve dynamics" associated with the changeover will be challenging. However, as the new radar network stabilizes, consistency of radar-rainfall estimates should improve.

References

Atlas, David
1990 *Radar in Meteorology*. Boston, Mass.: American Meteorological Society.

Denning, James
1994 "When a Levee Breaks," *Civil Engineering* 64(1).

Groisman, Pavel Ya. and David R. Legates
1993 "The Accuracy of United States Precipitation Data," *Bulletin of the American Meteorological Society* 75(3).

National Weather Service Central Region
1993 *Preliminary Report: Midwest Floods*.

PEAK TIMING OF MAJOR RAINFALL EVENTS, ALBUQUERQUE, NEW MEXICO

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Introduction

The City of Albuquerque, New Mexico, and the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) have adopted common Development Process Manual (DPM) standards that satisfy Federal Emergency Management Agency (FEMA) flood protection standards. Albuquerque has pursued basic hydrologic field research, literature review, and computer code development in pursuit of appropriate design and consistent methods. The process is ongoing.

For lack of better evidence, the DPM design hyetograph was specified with conventional NOAA-type intensities. Local engineering experience indicated that convective storms have a 30-minute time to peak intensity, t_p. FEMA instructed the City to place t_p in the second hour, a compromise between the City's practice and the SCS 12-hour t_p convention. This timing has design implications, as later peaks rainfall causes a higher peak runoff. This study addresses the following question: At what time after rainfall initiation do storms achieve peak intensity?

Terminology

Periods of 1 hour or more without rainfall identify the initiation and the secession of a rainfall event. In a simple sense, an event starts when measurable precipitation occurs after a dry hour and ends when a 1-hour dry period follows. Were the 1-hour criterion substantially shortened, major storms that pause for 30 minutes would become two independent events. Were the 1-hour criterion substantially lengthened, a brief, minor sprinkle some hours before an intense storm would cause the storm to appear protracted.

Major storm events exceed 1 inch, greater than the 0.6 inch annual event, but less than the 100-year storm, roughly 2 inches.

For consistency, this study uses the maximum 5-minute intensity as the peak intensity. Where a record is at other than 5-minute steps, linear interpolation yields the maximum 5-minute depth.

Data Base

This study draws from six New Mexican data sources. The ARS Experimental Watershed Program maintained six recording gages in the 1960s and 1970s (ARS, 1958; ARS, 1960; ARS 1963-89). Forty-one major events were digitally recorded, generally with 5-minute resolution.

A U.S. Geological Survey urban hydrology gaging project began in 1976 (Fischer et al., 1984; Metzker et al., 1993). Not all gages operated over the full period. The USGS data set includes 44 major events at nine watersheds in the Albuquerque metropolitan area. USGS records are digital, generally with 5-minute resolution.

AMAFCA has several years of raw printout record from the USGS urban hydrology gaging project newer than, or not reported in, Metzker et. al., (1993). The AMAFCA data set documents five major events.

The U.S. Army Corps of Engineers compiled mass rainfall curves with resolution of approximately 30 minutes from 1904 to 1942. Given the rapid intensity changes at 5-minute increments common in the USGS and ARS digital records, the smooth, linear Corps analog records appear to be grossly simplified. The Corps data describe major 40 events. The most extreme event, 10.1 inches in 6 hours, 21.25 inches overall, is "Unofficial." The Corps *Design Memorandum #1, Hydrology, Santa Fe River and Arroyo Mascaras* refers to "2.1 inches in 1 hour" on July 25, 1968. While records such as these two do not include sufficient data for t_p assessment, they contribute to a general appreciation of peak rates.

La Vigne (1988) evaluated NOAA microfiche continuous daily strip charts, Albuquerque International Airport, 1945-1984, and analyzed the 40 largest for frequency. Of these, five are major events. The NOAA data set is from 24-hour strip charts, providing resolution of approximately 15 minutes.

Burnett (1980) analyzed continuous strip chart recordings and Fisher Porter 5-minute increment punched tapes from the Albuquerque International Airport, 1951-1979. Only four events are major. Of these, three are redundant with the NOAA data set, given slight differences in visual readings. Burnett included records from private observers operating recording gages. One event in this category is major.

Statistical Summary

The 40 Corps major events are of poor quality and are not applicable for t_p analysis. Summary statistics for the 96 remaining major events are shown on the next page.

Variable	Min.	Max.	Mean	St. Dev.
Time to peak	0.02	2.83	0.67	0.63
Precipitation	1.00	5.06	1.72	0.85
Base time	0.37	10.08	3.59	2.62
Intensity	0.36	24.36	4.04	3.84

The correlation matrix is

Time to peak	1.000			
Precipitation	0.0872	1.000		
Base time	0.3971*	0.0916	1.000	
Intensity	-0.2936*	0.5535	-0.3773*	1.000

where * indicates significance at the 0.05 level. Major events having t_p less than 1 hour comprise 78% of the sample.

Spatial Distribution

Of the 96 total, 68 of the major events are at Albuquerque. The ARS Albuquerque watersheds are on the northwest mesa. All but four of the USGS major events are in the northeast heights. The NOAA airport data represent the southern portion of the city. The Albuquerque events cover the metropolitan area.

As Albuquerque data document few events of the 2-inch range, the addition of surrounding locations helps build a stratified sample. Following are summary t-test statistics by location indicating probabilities that the t_p data at other locations is statistically consistent with the Albuquerque population.

Location	t_p (hr)	t	p
Albuquerque	0.71		
Mexican Springs	0.40	1.2923	0.200
Santa Fe	0.24	0.9851	0.328
Santa Rosa	0.70	0.0566	0.955

Mean t_p's for Albuquerque and Santa Rosa are the same, confirmed by the high p value. Less can be statistically generalized about Mexican Springs and Santa Fe, as they have smaller sub-sample sizes, but the two are within the range of the Albuquerque values.

Santa Rosa has higher intensities than does Albuquerque (8.85 vs. 2.70 in/hr), but t_p's in both locations are again similar. Both locations demonstrate a reciprocal relationship between t_p and intensity. The harder the storm, the sooner the peak. Drizzles may not peak for several hours.

Storms that last 6 hours tend to peak relatively later than short storms, a logical relation. The very largest storms peak sooner than do the smaller events, but with little correlation. Overall, storm duration and t_p are unrelated.

While the non-Albuquerque locations show some different storm characteristics, the t_p attributes are effectively the same. Inclusion of ARS major events more than doubles the sample count above 2 inches and the sample count exceeding 5 in/hr intensity.

Joint Probabilities

There is no standard rule in hydrologic statistics regarding the application of joint probabilities. Is a 100-year event a storm with a 0.01 probability regarding depth, but a typical probability regarding timing? Should the timing also reflect extreme behavior? An answer requires knowledge of covariance. If t_p and depth are truly independent, a 100-year depth with a 100-year extreme t_p would describe a storm expected on the average every 10,000 years. If, on the other hand, depth closely correlates with t_p, the combination could be a 100-year storm.

The reasonable and conservative conclusion is that for major events, t_p is weakly related to depth. As correlation is minimal, the 100-year event should have a 100-year depth with an average t_p, 40 minutes in this case.

A Statistical Model

Regressing t_p upon depth P, base time t_b, and intensity i,

$$t_p = 0.359 + 0.1898\ P + 0.0595\ t_b - 0.0567\ i$$

where t_p and t_b are in hours, P is in inches, and i is in in/hr. Multiple R^2 is 0.47. The signs of the coefficients agree with the visual slopes; t_p increases with P and t_b and decreases with i.

Statistical test does not justify such a model, however. The independent variables have minimal verified relationship to t_p. Regression helps, however, to view sensitivity and to compute particular estimates. For the mean Albuquerque 100-year 6-hour event, P is 2.51 inches, t_b is 6 hours, and i is 6.94 in/hr. Regressed t_p is 0.80 hours, somewhat higher than the overall mean, but given the scatter in the data base, a close value. The statistically legitimate best estimate of t_p is simply the overall mean, 0.67 hours.

The Event of August 14, 1980

Of the USGS major events, five are for the storm of August 14, 1980, in different watersheds. Of these, the smallest total depth is 2.07 inches. Thus, this storm resembles the 100-year event. The t_p occurred at 1.25, 0.67, 0:75, 1:42 and 1.25 hours. As an alternative to a statistical model drawn from the complete data base, design t_p could be based on this historic record. Were the historic-event approach favored, the August 14, 1980, event t_p is 1.07 hours. A single event is a poor criterion when a broader data set is available. Neither the storm of August 14, 1980, nor any other unique phenomenon should be a sole justification for a standard.

Assignment of Time to Peak

Various estimates of t_p are

t_p (min)	Estimate
30	Pre DPM engineering practice in Albuquerque
40	Data base overall mean
48	Data base regression
64	Storm of August 14, 1980
84	DPM, 8/91
360	SCS II-a, NM

Of the above estimates, this study proposes the 48-minute value for the next DPM revision. A broad data base substantiates this value. This value is reasonable in light of alternative estimates.

Maximum 5-Minute Depths

The P_5/P ratio has a mean of 0.20 and a standard deviation of 0.15, where P_x is x-minute depth. The Miller et al. (1973) P_5/P is 0.24. Given the variance of the data base, the difference is of minimal significance. Exact differential significance cannot be calculated without knowledge of Miller's variance. The four Albuquerque precipitation zones in the DPM average a 0.82 ratio between the P_{60} and the 6-hour depth. Thus the data base P_5/P_{60} is $0.20/0.82 = 0.24$. Miller establishes 0.29 as the P_5/P_{60} ratio.

Hyetograph Sequencing

Hyetograph sequencing is the process of assigning single time-step rainfall depths to the hyetograph array. To preserve the maximum depth-duration relationships, the maximum depth is assigned to the time step containing t_p. The next highest depth is assigned to the immediate left or right member of the array. The next highest depth is assigned to the immediate left or right of the latter pair (Cudworth, 1989)

Rainfall depths before the peak 5 minutes and before the peak 15 minutes were determined for 91 digitized major events and converted to ratios of total precipitation. The mean ratios are:

Ratio	Mean	St. Dev
P before peak 5 min/P total	0.27	0.18
P before peak 15 min/P total	0.16	0.15

As with 5- and 15-minute depths, the above means may be divided by 0.82 to estimate the ratios to P_{60}. To preserve the above bracketing and the t_p assignment, the time step of maximum depth must be 45-50 minutes, followed and preceded by the second and third greatest depths, respectively. Sixteen percent of the total rainfall must occur in the first 40 minutes.

References

Agricultural Research Service

1958 *Annual Maximum Flows from Small Agricultural Watersheds in the United States*. Washington, D.C.: U.S. Department of Agriculture.

Agricultural Research Service

1960 *Selected Runoff Events for Small Agricultural Watersheds in the United States*. Washington, D.C.: U.S. Department of Agriculture.

Agricultural Research Service

1956-1979 *Hydrologic Data for Experimental Agricultural Watersheds in the United States*. Misc. Pubs. 941963, 991965, 10701968, 11641970, 11941971, 12161972, 12261972, 12621973, 13301976, 13701979, 13801979, 13831980, 14121981, 14201982, 14371983, 1446984, 14511986, 14541987, 14691989. Washington, D.C,: U.S. Department of Agriculture.

Burnett, B.
1980 *The Development of a Rainfall Hyetograph for Albuquerque, New Mexico.* Albuquerque, N.M.: Department of Civil Engineering, University of New Mexico.

Cudworth, A.G., Jr.
1989 *Flood Hydrology Manual.* Denver, Colo.: U.S. Bureau of Reclamation.

Fischer, E. E., J. J. Rote, and P. Borland
1984 *Rainfall-Runoff Data in the Albuquerque, New Mexico Metropolitan Area, 1976-83.* Open File Report 84-448. Albuquerque, N.M.: U.S. Geological Survey.

La Vigne, P.
1988 *Study of Rainfall Events for Albuquerque, New Mexico.* Albuquerque, N.M.: Department of Civil Engineering, University of New Mexico.

Metzker, K. D., Gold, R. L. and Thomas, R. P.
1993 *Rainfall and Runoff Data for the Albuquerque, New Mexico, Metropolitan Area, 1984-88.* Open File Report 92-653. Albuquerque, N.M.: U.S. Geological Survey.

Miller, J. F., R. H. Frederick, and R. J. Tracey
1973 *Precipitation-Frequency Atlas of the Western United States, Vol IV-New Mexico.* Silver Spring, Md.: National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

Tarleton, L.
1993 Letter of Cliff Anderson, Albuquerque Metropolitan Arroyo Flood Control Authority. May 3.

A COMPARATIVE STUDY OF RETURN PERIODS FOR 24-HOUR PRECIPITATION FROM TWO CONSECUTIVE 30-YEAR PERIODS (1930–1959 AND 1960–1989)

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Introduction

With the current debate over climate change, there is an interest in updating climate studies that were done over 30 years ago. Studies such as TP-40 (Hershfield, 1961) are based on data from before 1960. Since then, another 30 years of data have been collected. This study used a graphical approach to determine if there is an important difference in the frequency of 24-hour rainfall from two consecutive 30-year periods (1930–1959 and 1960–1989). A set of maps was made for each period. Each map was a plot of the 24-hour rainfall for a specific return period (10, 25, and 50 years). A comparison of the map pairs for each return period was expected to give an indication of the change, if any, in the rainfall frequency values during the latter period.

Situation

Although climate change is a popular topic in the environmental field today, the actual extent of climate change and its importance to persons working in related fields is debatable. The climatic record is short, with most data covering less than 100 years. With such a short span of time for comparison, there was interest in making use of the most recent data available in environmental design and planning.

Engineers, planners, floodplain managers, and other professionals concerned with environmental matters use rainfall frequency data. Much of the rainfall frequency information available was based on studies done prior to 1962. The Weather Bureau Technical Paper Series (U.S. Weather Bureau, 1955, 1956, 1958) was an example.

Two questions that this study addresses are: Do studies like TP-40 need to be redone using more recent data or longer periods of record? and, Are these recent data more relevant for use today?

Method

This study used a method of computation similar to that used in TP-40. The precipitation data used were derived from the "Daily Precipitation" section of *Climatological Data* (National Climatic Data Center, 1930–1989). Precipitation amounts were for the 24 hours preceding observation time. All extreme precipitation events were assumed to be non-frozen; i.e., rainfall. In TP-40, a partial duration series was used. It was shown that for return periods of greater than 10 years the partial duration and annual series yielded the same return period values. An annual series consisting of the greatest 24-hour precipitation amount for each year was used in the computation of the return period values. The annual series was ordered, and the return periods were computed using Weibull's Formula (Lindsey et al., 1975, p. 340):

$$T_r = \frac{n+1}{m}$$

Where: Tr= the return period in years
n= number of values in the data set
m= rank order of magnitude in the data set; m=1 being the largest value and m=n being the smallest

When plotted on extreme value probability paper, the return period values approximated a straight line (Gumbel, 1958). The reduced variate was linear on the probability scale of the extreme probability plot and was related to the probability of exceedance by (Lindsey et al., 1975, p. 345):

$$P = 1 - e^{-e^{-y}}$$

Where: P= the probability of exceedance
e= the base of napierian logarithms
y= the reduced variate, a function of probability

For values greater than the mean (Tr > 2.33 year), a straight line was fitted to the plotted values using a least squares technique of simultaneous equations and Cramer's rule. A value for each return period of interest was then computed from this line and multiplied by 1.13 to adjust from 24-hour to 1440-minute values (Hershfield, 1961).

Construction of Maps

Return period values for 27 stations in South Carolina, North Carolina, and Georgia were plotted on six maps, one pair for each return period of 10, 25, and 50 years. These maps were analyzed, and isohyets were drawn. The resulting regional rainfall frequency maps are similar to those in TP-40 (Figures 1 and 2).

Conclusions

Comparison of the map pairs indicated lower return period values in the most recent 30-year period (1960–1989) for most of South Carolina. However, there was an increase in the eastern portion of the state. The amount of difference in the two data periods increased with the return period. A conclusion may be drawn that there was a difference in the rainfall frequency values for the two subsequent 30-year periods with the latter 30-year period yielding lower values over most of the state. An explanation of the increase in a small portion of the study area was beyond the scope of this graphical analysis. Perhaps a more sophisticated statistical study will yield answers. The total period of record was too short for drawing any conclusions as to long term climatic change, but new studies incorporating data for the entire period of record would obviously be of value.

References

Gumbel, E. J.
1958 *Statistics of Extremes*. New York: Columbia University Press.

Hershfield, D. M.
1961 *Rainfall Atlas of the United States*. Technical Paper #40. Washington D.C.: Weather Bureau, U.S. Department of Commerce.

Lindsey, R. K., M. A. Kohler, and J. L. H. Paulus
1975 "Probability in Hydrology: A Basis for Design." In *Hydrology for Engineers*, Second Edition. New York: McGraw-Hill Book Company.

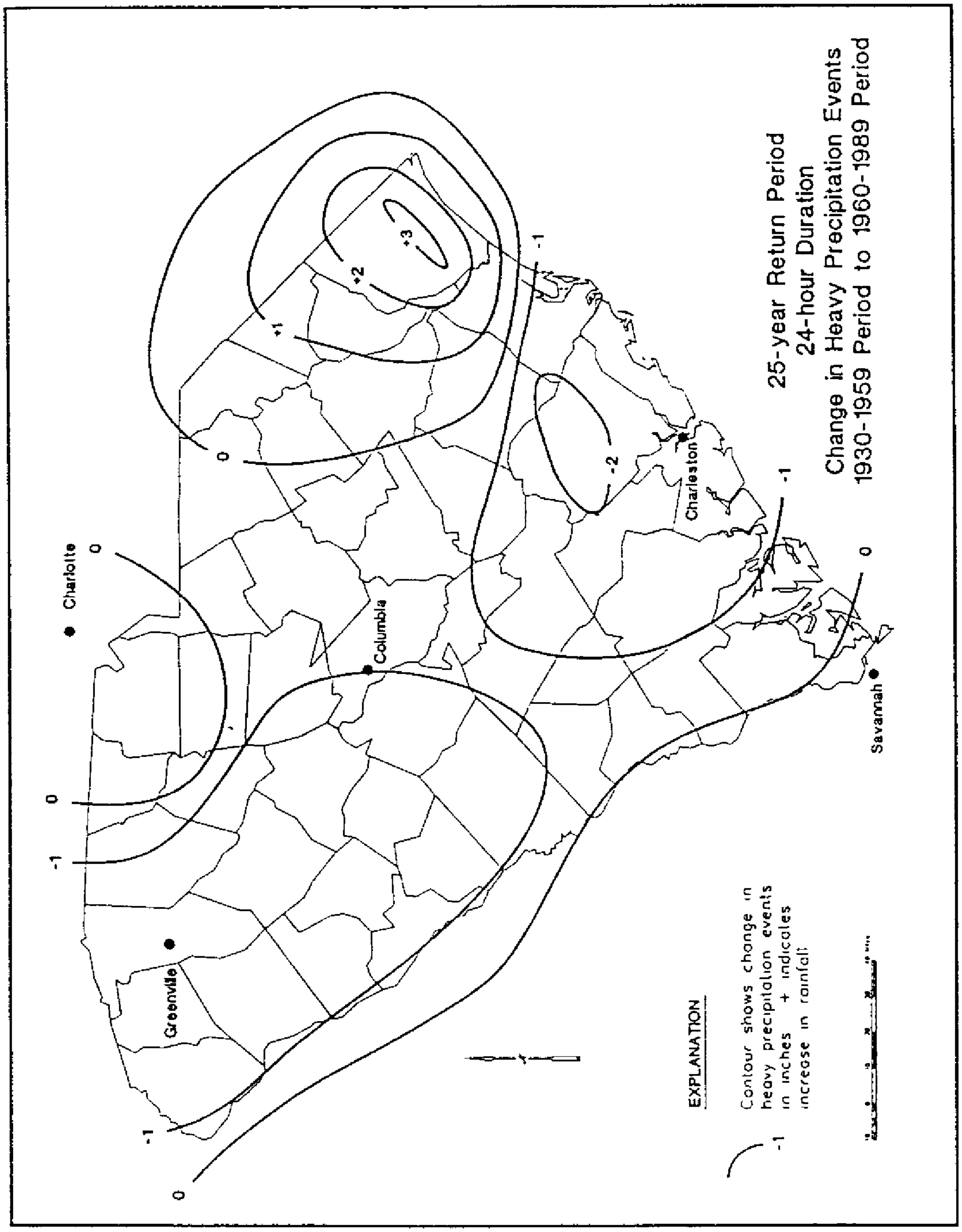

Figure 1. *Twenty-five year return period.*

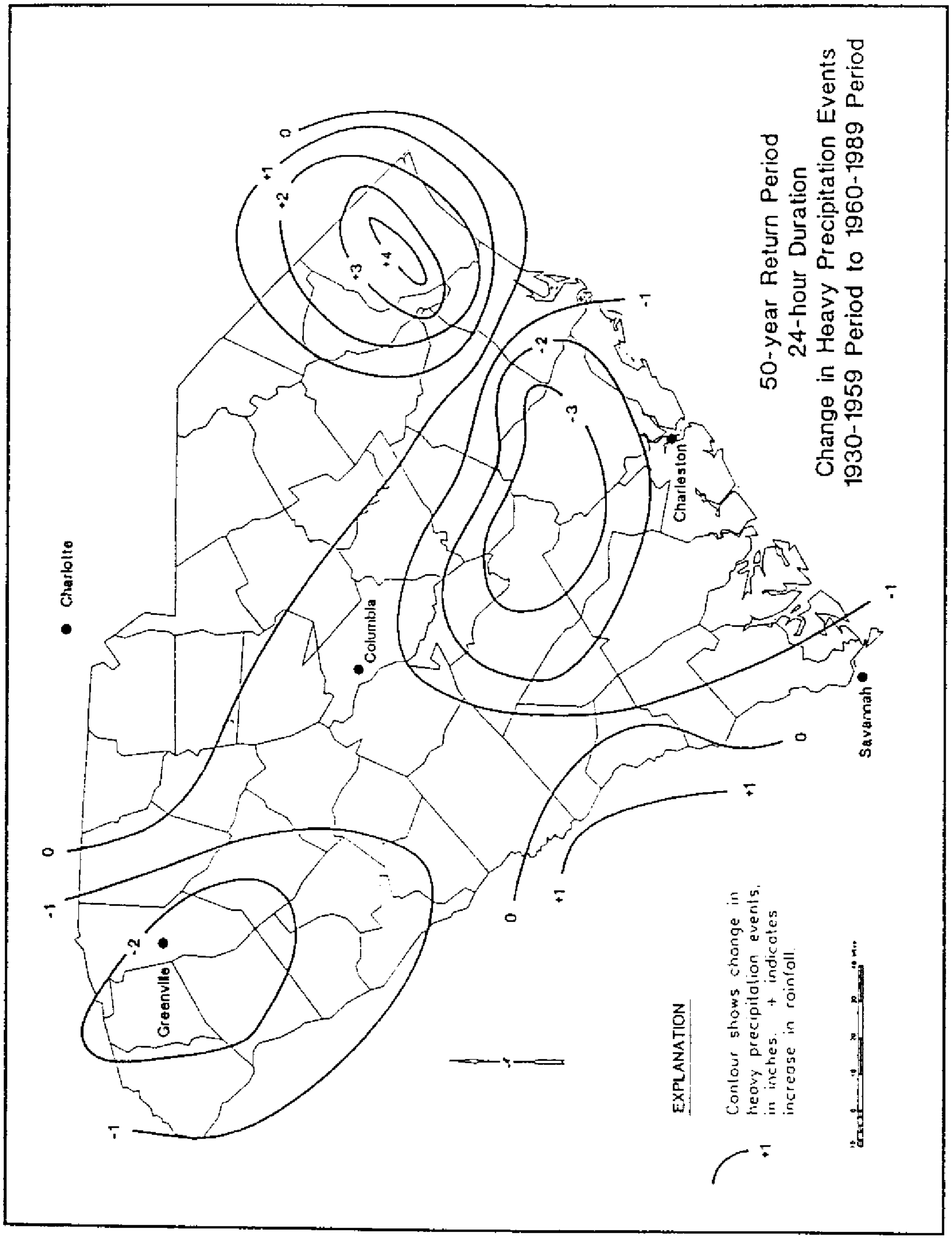

Figure 2. Fifty year return period.

National Oceanic and Atmospheric Administration
1930-1989 Climatological Data. Asheville, N.C.: National Climatic Data Center.

U.S. Weather Bureau
1955 *Rainfall Intensity-Duration-Frequency Curves for Selected Stations in the United States, Alaska, Hawaiian Islands and Puerto Rico.* Technical Paper #25. Washington, D.C.: U.S. Weather Bureau.

U.S. Weather Bureau
1956 *Rainfall Intensities for Local Drainage Design i Western United States.* Technical Paper #28. Washington D.C.: U.S. Weather Bureau.

U.S. Weather Bureau
1958 *Rainfall Intensity-Frequency Regime.* Technical Paper #29, "Part 2: The Southeastern United States." Washington D.C.: U.S. Weather Bureau.