ANALYSIS OF RELATIONSHIPS BETWEEN LIGHTNING, PRECIPITATION, AND RUNOFF

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DISCLAIMER

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ABSTRACT

More than 70% of the total annual precipitation in New Mexico can be produced by convective thunderstorms during the "monsoon season" of June through September. These thunderstorms generally are accompanied by intense lightning and characteristically produce heavy, localized rainfall often resulting in flash floods. The technology for locating cloud-to-ground lightning strikes has the potential to pinpoint these intense precipitation events as well as quantify the volume of water associated with them. This documents the spatial and temporal variability of this phenomena over large scales and can also be used for real-time flood forecasting in critical areas. This study developed algorithms between lightning and precipitation depth, used lightning data to determine rainfall depth for input to a distributed parameter hydrologic model, and tested the model to predict discharge. There was a significant correlation between rain-gauge measured precipitation and lightning within a 3 km radius of the gauge location. Precipitation prediction was greatest using regressions that included lightning strikes and relative humidity. The preliminary hydrologic modeling reinforced the need for future research to improve the estimate of spatial and temporal characteristics of lightning related precipitation events. Lightning location technology, combined with a Geographic Information System (GIS) approach, has potential value for defining the spatial and temporal resolution of intense, summer precipitation patterns.

Keywords: Atmospheric Processes, Climate, Rainfall, Rainfall-Runoff Models, Weather Data Collection

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INTRODUCTION

Lightning during thunderstorms is a result of the strong electric fields produced by large-scale charge separation due to convective motion and precipitation in the thunderstorm. Although the exact mechanism by which charge is separated is still a topic of active research, the generally accepted theory of thunderstorm separation is driven on a large scale by differential sedimentation of precipitation particles (see Beard and Ochs 1986). In convective updrafts, moisture condenses as the air cools to well below freezing, forming ice crystals and graupel (small hail). In collisions between small ice crystals and larger graupel, negative charge is transferred from the ice crystals to the graupel. The terminal velocity of the graupel is greater than that of the ice crystals causing graupel to fall while ice crystals are transported upward. In this way, positive charge is carried to the top of the thunderstorm, while negative charge is carried to the base. This charge separation produces large electric fields in the cloud and between the cloud and ground. When the fields reach a threshold level, electrical breakdown (i.e., lightning) occurs, neutralizing the charge separated by precipitation. Since the physical processes responsible for precipitation are linked to intra-cloud charge separation, there should be a strong correlation between charge transferred by lightning and precipitation volume.

More than 70% of the total annual precipitation in New Mexico is produced by convective thunderstorms during the "monsoon season" of June through September. These thunderstorms are generally accompanied by intense lightning and characteristically produce heavy, localized rainfall which often results in flash floods. Recently, a technology for locating cloud-to-ground lightning discharges and measuring the lightning peak current and number of return strokes has been deployed throughout the western U.S. and is operated by the Bureau of Land Management's Boise Interagency Fire Center (BIFC). The objectives of this project were to establish algorithms which convert the number of lightning strikes and the power spectra of the lightning into rainfall depth, estimate rainfall depth for input to distributed parameter hydrologic models, and test these models ability to predict discharge accurately.

Realistic and accurate algorithms which convert the number of lightning strikes per area and the power spectra of the lightning into rainfall depth aids hydrologic analyses in at least three ways. First, lightning information fills gaps in existing rain gauge networks; that is, it may provide information on rainfall depth in sparsely gauged regions. In addition, large-scale water balance models, such as RIOFISH (Cole et al. 1990) can be enhanced to account for ungauged tributary inputs to New Mexico reservoirs. Second, lightning information may reproduce the spatial and temporal variability of rainfall at ungauged locations. That knowledge enhances rainfall-runoff, discrete-event hydrologic models that are sensitive to rain rates relative to infiltration rates. Third, once spatial and temporal information on rain depth is known for historic watershed events and a hydrologic model is calibrated to that data, incoming lightning data can be used for real-time flood forecasting in critical areas.

Precipitation is highly variable in arid regions. Generally, an inverse relationship exists between total annual precipitation and its spatial and inter-annual variability. Rainfall in New Mexico certainly reflects this pattern, with a majority of total annual precipitation coming in the form of convective thunderstorms during the months of June through September. On the Sevilleta National Wildlife Refuge (SNWR), for example, annual precipitation in any single year has been observed to range from 4 inches at one station to 12 inches or more at another, with low and high values shifting between gauges across years (Grover and Musick 1988). Without an inordinately high number of rain gauges, it is impossible to estimate the total and spatial distribution of precipitation in such a region with any accuracy.

The highly variable spatial distribution and intensity of summer rainfall in New Mexico and other arid regions begs for some economical remote sensing technique to estimate rainfall in remote areas. The only current alternative to a remote sensing system is a dense network of recording rain gauges that is monitored intensively. The recently established lightning location systems provide information necessary to develop a modeling/forecasting protocol. Cloud-to-ground lightning discharges are currently monitored by a network of lightning location sensors that record the time of a discharge, its location (to an accuracy of about 2 km), peak current, and the number of return strokes (Krider et al. 1980).

Lightning can be either intra-cloud (IC), or cloud-to-ground (CG). Studies by Battan (1965), Grosh (1978), Piepgrass et al. (1982) and Goodman et al. (1988) show proportionality between precipitation volume and the number of lightning flashes. These studies show about 7 x 10^3 m^3 of water for each IC flash, and 2 x 10^4 m^3 of water for each CG flash.

The next question is whether remote sensing of lightning produces sufficient information to exploit this relationship. Currently, remote sensing is done by magnetic direction finding. Lightning produces strong electromagnetic impulses that travel hundreds of kilometers. Using crossed-loop antennas, the direction to the lightning discharge can be determined. When two or more direction finders (DFs) record the same event, the lightning's location can be determined by triangulation. In addition to direction, the DF's record the strength of the signal. The current carried by the lightning can be estimated, given the strength of the signal and the distance to the source. Also, the number of return strokes in CG lightning can be recorded.

The DF network in the western US is operated by the Boise Interagency Fire Center (BIFC) to determine locations of lightning initiated fires. Because of BIFC's primary interest in forest fires, their network discriminates between CG flashes, which can ignite fires, and IC flashes. This network records only CG flashes; however, because of the approximately constant IC-to-CG ratio (about 4:1 in New Mexico, Prentice and Mackerras 1977), this data should give a good approximation of the total lightning activity of thunderstorms.

Concerning watershed modeling, the number of lightning strikes per unit time and cumulative number of strikes have been useful in predicting precipitation volume. This report converts this information into data for use in various types of hydrologic models. Hydrologic models may be simple linear regressions relating annual watershed precipitation to annual streamflow on perennial streams, or the models may be quite complex, distributed parameter, single-event, rainfall-runoff models for ephemeral streams. Hydrologic models may not necessarily be related to surface flow, but instead may be used to account for soil moisture of ground water recharge. In any case, knowledge of the temporal and spatial characteristics of the precipitation input record is necessary for model performance. The better this knowledge becomes, the less uncertainty in the model forecasts, assuming, of course, that the model structure and processes adequately emulate natural structure and processes. If the model accurately represents the natural system, then better rainfall input data should produce better model forecasts.

The scale at which lightning data-to-precipitation algorithms can aid model forecasts is not entirely clear. At small scales of a few hectares, it is expected that runoff estimates from lightning data will be quite good. At large scales of hundreds of square kilometers, other processes, such as channel storage of surface flow, may create errors in the estimation of discharge. However, as confidence grows with estimates at small and intermediate scales, then the apparent errors at large scales may be attributed to inadequately modeled processes, that create significant departures between observed and estimated discharge. Therefore, it is advantageous to start at smaller scales and work toward larger scales.

In this study, a single event, distributed parameter, rainfall-runoff model was applied to gauged watersheds in the Southwest. These gauged watersheds were selected on the basis of data availability, data quality, and modeling complexity. This last criterion is important because the goal of this study is to test the use of lightning data, not the performance of any one particular model.

In summary, lightning data is easily obtained and can be combined readily with a Geographic Information System (GIS) containing rain gauge locations, watershed boundaries, and watershed properties affecting runoff (e.g., slope, depth to bedrock). We determined whether relationships between lightning and precipitation depth could be used to enhance the utility of surface hydrologic models. Also, in many areas of the Southwest, rain gauges are too widely dispersed to provide accurate estimates of spatial variability and total rainfall in large river basins (e.g., Pecos Valley). Statistical models predicting rainfall amount, intensity, and potential recharge or runoff on the basis of remotely sensed lightning discharges will be useful for predicting flash floods, moisture availability in isolated rangelands, and possibly improving estimates of watershed-wide runoff or recharge.

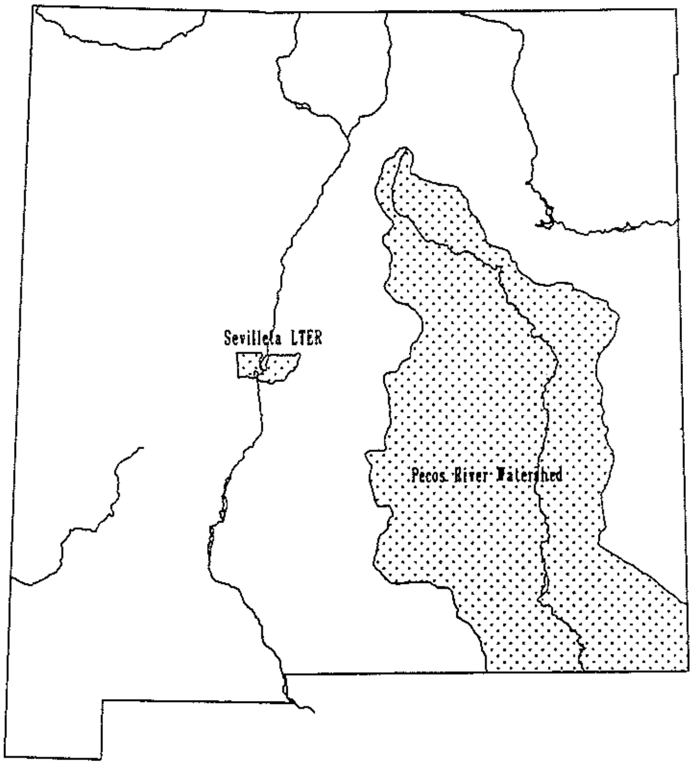


Figure 1. Map of New Mexico with Sevilleta National Wildlife Refuge (SNWR) and Pecos Watershed delineated.

METHODS

Lightning

Lightning location data for the state of New Mexico and vicinity were made available to New Mexico Institute of Mining and Technology (NMIMT) by the BIFC on a near real-time basis. Data were subsequently transferred from NMIMT to University of New Mexico (UNM) via Internet. Each data file consisted of all cloud-to-ground lightning strikes during a 24-hour period. Each observation or line of data contained: 1) time of the strike in Greenwich Mean Time (GMT) 2) latitude and 3) longitude of the strike, 4) maximum field strength, 5) number of return strokes in the strike, 6) a code denoting accuracy of the strike, 7) the DF stations detecting the strike and 8) the time stamp of when the data was received by NMIMT. Table 1A shows an example of a raw file. The second through the sixth lines are diagnostic lines that should be removed in editing. At UNM, data were passed through an editing program called "LLPEDT." LLPEDT examined each observation to determine if it had valid entries for all of the above mentioned fields. Any observations that did not have valid entries were collected into a "bad" file. These lines could then be edited either automatically and/or manually. Lines that could not be corrected were eliminated from the file. Lines that could be fixed were corrected and reinstated into the original file to create a "good" file. This file was then passed to another program which 1) added year and Julian day variables, 2) converted GMT to MST (Mountain Standard Time), 3) removed the last two variables (recording stations and the time stamp) and 4) clipped any lightning outside the rectangle defined by the four extreme corners of the state. This created an "ed.prn" file (Table 1B) which could then be passed to a variety of displaying,

Table 1A. Example of raw lightning location data as received by NMIMT from BIFC.

```
/* Sat Jun 13 00:00:01 1992 MDT     Sat Jun 13 06:00:01 1992 GMT */
^A*STATUS  08:24:12 MDT
^A*TIME  08:24:24 MDT
^A*SELFTEST  08:24:32 MDT
^A*STATUSD  08:25:00 MDT
^A*STATUS  08:25:11 MDT
21:35:44.732   33.717   -103.328    -16.1   1  T   24,16     14:57:46 MDT
21:36:13.757   33.720   -103.276    -17.3   4  T   24,16     14:58:15 MDT
21:39:09.037   33.748   -103.142    -17.4   2  T   24,16     15:01:11 MDT
21:59:26.366   33.902   -103.242    -24.3   1  T   24,16     15:21:28 MDT
22:02:38.888   31.867   -103.886    -22.5   1  T   24,27     15:24:41 MDT
22:46:55.932   33.221   -103.291    -22.8   6  b   24,16     16:08:57 MDT
23:01:50.786   33.131   -103.099    -30.5   1     24,16,27   16:23:52 MDT
23:05:56.200   33.439   -103.320    -13.4   1  T   24,16     16:27:58 MDT
23:10:23.921   33.512   -103.233    -32.2   3  T  24,25,16   16:32:26 MDT
23:16:39.373   33.126   -103.106    -19.4   1  T   16,27     16:38:41 MDT
23:19:50.948   33.169   -103.012    -34.4   1     24,16,27   16:41:53 MDT
23:21:23.278   33.177   -103.024    -22.2   1  T   16,27     16:43:25 MDT
23:21:52.469   33.218   -103.188    -21.8   1  T   16,27     16:43:54 MDT
23:22:07.057   33.286   -103.683    -21.0   1     24,16,27   16:44:09 MDT
23:22:59.744   33.285   -103.371    -20.2   1  T   16,27     16:45:01 MDT
23:23:09.215   33.181   -103.162    -22.7   1     24,16,27   16:45:11 MDT
```

Table 1B. Example of same lightning location data as in table 1A after processing through LLPEDT program.

```
1992 165  14:35:44.732   33.717  -103.328   -16.1   1 T
1992 165  14:36:13.757   33.720  -103.276   -17.3   4 T
1992 165  14:39:09.037   33.748  -103.142   -17.4   2 T
1992 165  14:59:26.366   33.902  -103.242   -24.3   1 T
1992 165  15:02:38.888   31.867  -103.886   -22.5   1 T
1992 165  15:46:55.932   33.221  -103.291   -22.8   6 B
1992 165  16:01:50.786   33.131  -103.099   -30.5   1 A
1992 165  16:05:56.200   33.439  -103.320   -13.4   1 T
1992 165  16:10:23.921   33.512  -103.233   -32.2   3 T
1992 165  16:16:39.373   33.126  -103.106   -19.4   1 T
1992 165  16:19:50.948   33.169  -103.012   -34.4   1 A
1992 165  16:21:52.469   33.218  -103.188   -21.8   1 T
1992 165  16:22:07.057   33.286  -103.683   -21.0   1 A
1992 165  16:22:59.744   33.285  -103.371   -20.2   1 T
1992 165  16:23:09.215   33.181  -103.162   -22.7   1 A
```

plotting or buffering programs.

While lightning data for the entire state of New Mexico were collected and processed, the two areas of particular interest to this study were the Sevilleta National Wildlife Refuge and the Pecos River watershed (Fig. 1). Determining the number of lightning strikes within these areas (buffering) could be performed by two methods. These included a C program entitled "LLPCN" which was quickest at determining the number of lightning strikes occurring within a specified distance around a point of interest (e.g.,a precipitation gauge). Circles of any desired radius could be selected for any number of locations specified in latitude and longitude. The LLPCN program would output the number of strikes which occurred within those circles for the period of time specified. This program could also be used to buffer areas of other regular shaped polygons. However, irregular shaped areas, such as the Sevilleta or watersheds proved to be more difficult to buffer. A simplified means of getting lightning strikes for the Sevilleta involved buffering a rectangle which just enclosed the refuge boundaries. One solution would have been to split the total area into a number of regular shaped polygons with the summation of strikes in individual polygons approximating the sum for the total area. This method was attempted but soon abandoned. For a watershed such as the Rio Salado, it was found that two 5th order polynomial curves could be used to approximate its boundary. Figure 2 shows how these polynomial curves compare to that of the actual boundary. This method was not tried for the Pecos watershed.

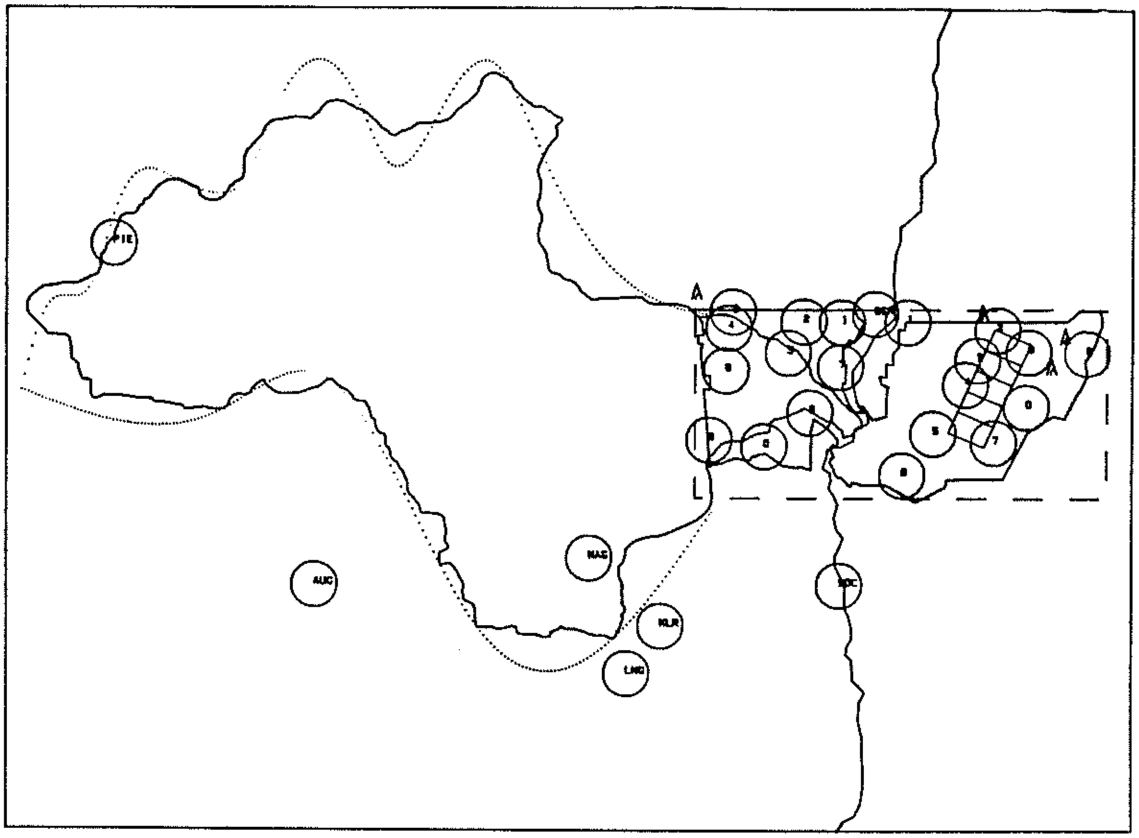


Figure 2. Map of Sevilleta National Wildlife Refuge and Rio Salado watershed. Solid lines delineate digitized Rio Salado boundaries while dotted lines indicate boundaries as defined by two 5th order polynomial curves. The dashed rectangle was used to buffer Sevilleta lightning.

The ideal means of buffering irregular shaped areas was provided by GIS. GIS is well suited to doing spatial analysis of such things as lightning and precipitation distribution. The GIS currently used by the Sevilleta LTER is ARC/INFO 5.0 which is being run on an ULTRIX 4.2 platform on a DEC 3100 workstation. This will soon be upgraded to ARC/INFO 6.0 running on a DEC 5000. Using each edited file, daily coverage files were created for the entire state for 1989 through 1991. In these coverages, each lightning strike carries with it its full complement of attributes (i.e., number of return strokes, field strength, time, etc.). Map extents or boundaries of areas of interest (such as the Sevilleta and Pecos Watershed) have been developed in ARC, the plotting or mapping portion of ARC/INFO. The boundaries for the Sevilleta were produced through digitizing a 7 1/2 minute USGS topographic maps while the boundaries for the Pecos watershed were digitized from New Mexico in Maps (Snead 1986) at a much coarser scale. Figure 1 shows the two areas of interest as mapped by ARC.

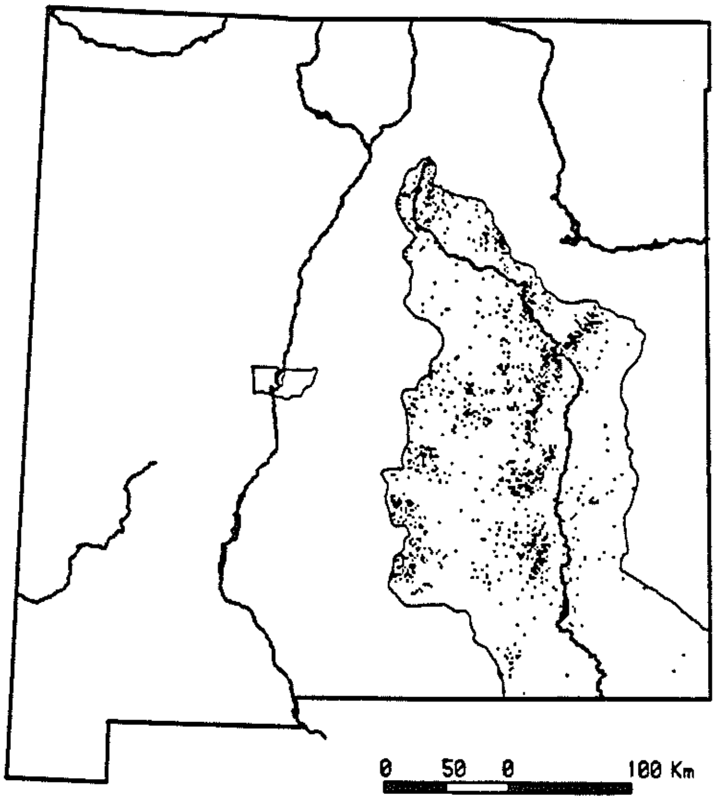
To obtain the number of lightning strikes within a specified area, the map coverage of these areas is essentially used as a cookie cutter to clip the lightning strikes within the boundaries of these areas out of the coverage of the entire state. These data are output in tabular form from INFO, the data managing portion of ARC/INFO. This process would be quite tedious if not for a module within ARC/INFO termed Arc Macro Language (AML). AML provides the capability of developing batch command files (also termed AMLs) which allows automation of the above process. Menu driven AMLs can be developed to clip the daily coverages for any desired area for any time period. For this study, an AML (also entitled LLPCN) can clip coverages for the Sevilleta National Wildlife Refuge and the Pecos watershed as well as several other areas of interest.

Programs for displaying and plotting lightning strikes have been developed for both MS-DOS and UNIX operating systems. The most sophisticated programs use the lightning coverages developed in ARC/INFO and allows them to be overlaid with any other coverages that have been developed for the region. For the Sevilleta, such coverages include road networks, drainage networks, precipitation gauges, elevation and soils. Figures 3A and 3B show examples of output from this package.

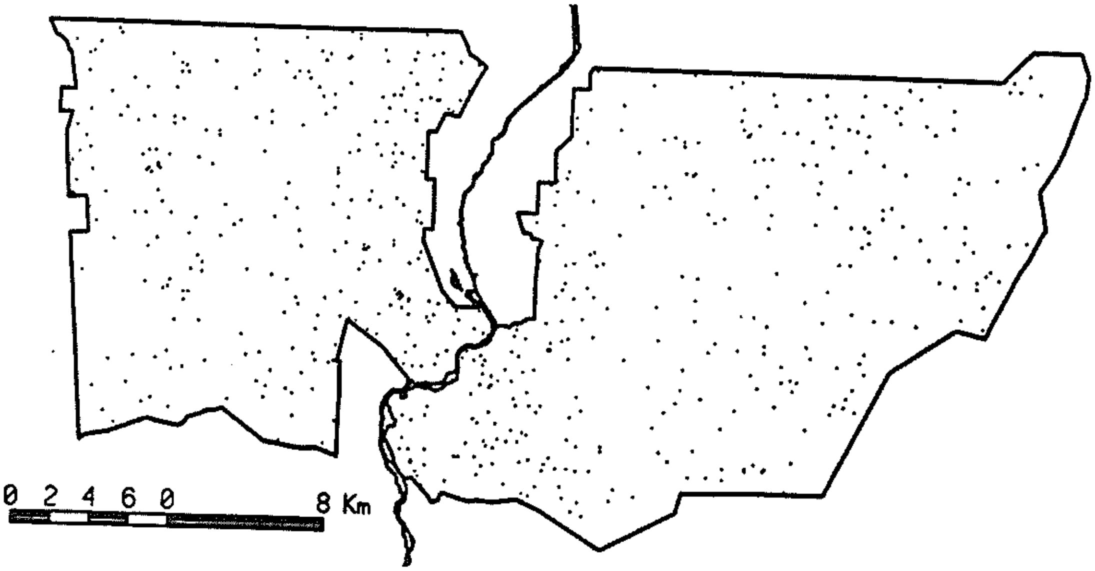
A second UNIX-based plotting package named PLOT2D has been developed within another graphics package (KHOROS) developed by the University of New Mexico's Computer Engineering Department. This program enables rapid display lightning for any given number of days for various areas of interest. Figures 4A and 4B show examples of output from this package.

A third display and plotting program has been developed for MS-DOS machines using a menu-driven PASCAL program. This program named "LLPLOT" works only on a single day's lightning file although multiple days can be concatenated for multiple day plots. One of several different map areas of display can be selected from a menu and the operator can start and stop the lightning strike plotting on the display. While the lightning files can be stored on the DOS machine, the files' size makes it more practical to store files on the UNIX system. Using an ethernet card coupled with a package such as PC-NFS allows us to mount the UNIX drives. This makes the PC capable of using data directly off the UNIX system. Figures 5A and 5B demonstrate plotted output from this package.

Data archival required additional data processing. This involved combining all daily files into annual files using a program entitled LLPCHK. Daily files were then extracted from the larger files (using LLPEXTR) with the desired cutoff time (12 midnight MST). Currently, New Mexico lightning data for 1989, 1990, and 1991 have been edited and archived in a database format in SIMS (Sevilleta Information Management System). Lightning data for a smaller area of New Mexico from 1988 have also been archived.



(A) Pecos River Watershed



(B) Sevilleta National Wildlife Refuge

Figure 3. Example of lightning strikes mapped for a one day period through ARC/INFO for (A) the Pecos Watershed and for (B) the Sevilleta National Wildlife Refuge.

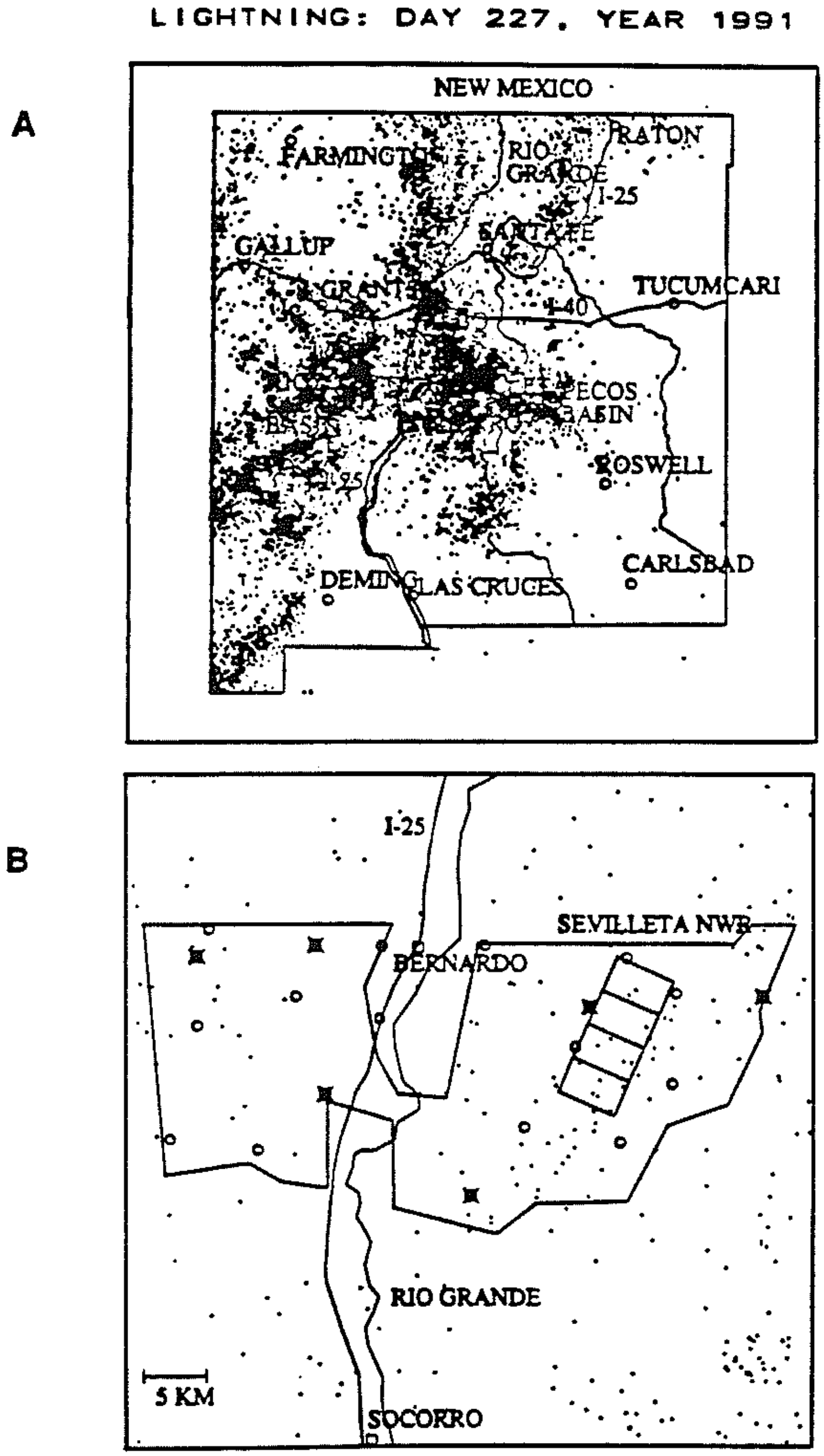


Figure 4. Lightning strikes mapped using KHOROS graphics package for August 15, 1991 for (A) New Mexico, and (B) the Sevilleta National Wildlife Refuge.

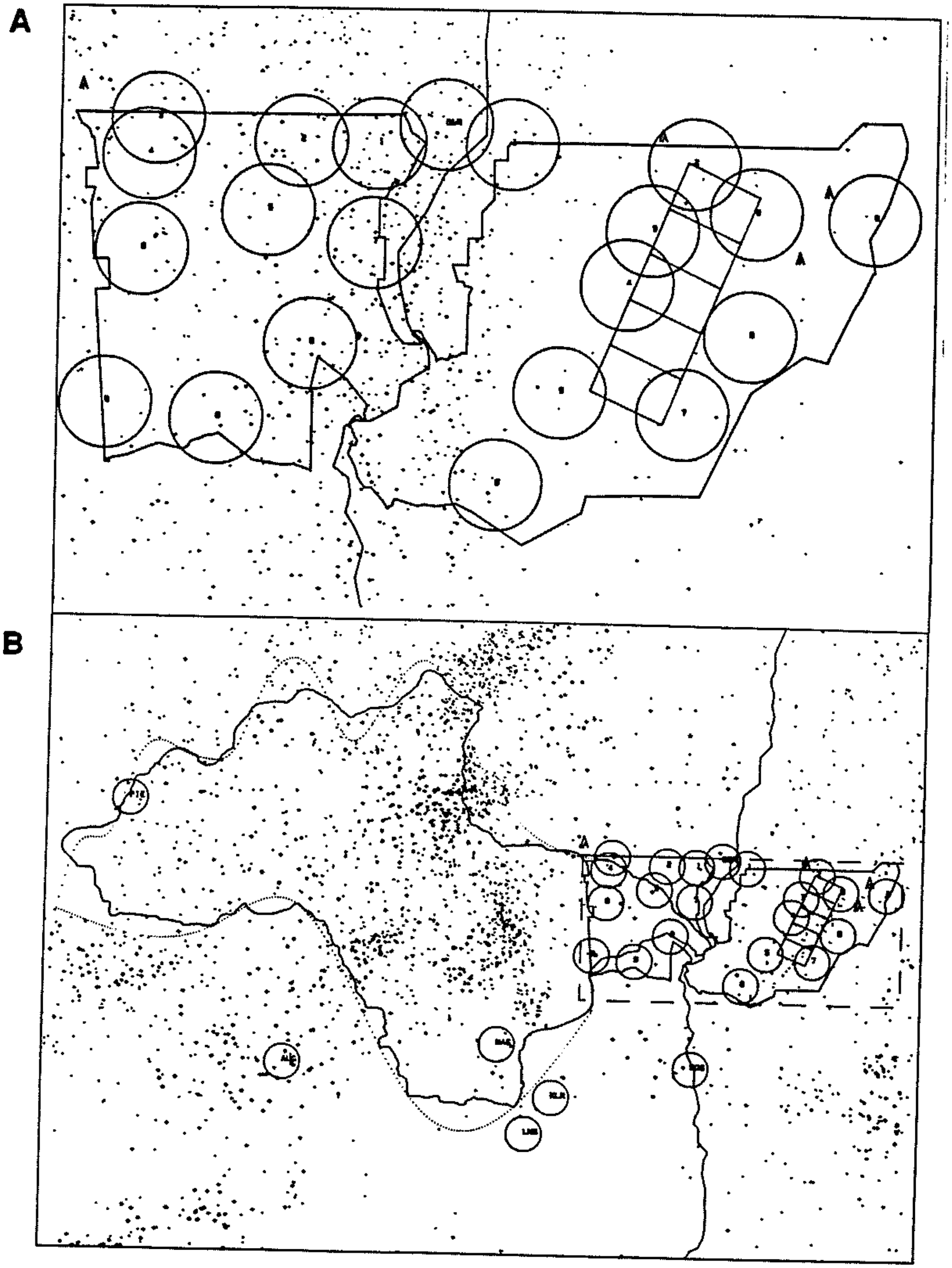


Figure 5. Lightning strike data mapped by MS-DOS program LLPLOT for (A) the Sevilleta and (B) the Sevilleta and Rio Salado Watershed. Circles denote 3 km buffers around precipitation gauges.

Precipitation

Sevilleta

Precipitation was measured by a continuously increasing network of precipitation gauges on the Sevilleta NWR and surrounding areas (Fig 6). Installation of the precipitation gauge network was begun in early 1989. Automated meteorological stations, equipped with tipping bucket gauges (.01" per tip), collected hourly measures of precipitation as well as other concurrent meteorological data. During 1990 and 1991, precipitation was collected on a one minute basis. Twenty funnel gauges, designed to collect bulk precipitation for chemical analysis, were also established in early 1989. These samples were collected and measured on approximately a monthly basis depending on the frequency of storm events.

Tipping buckets were monitored by two types of dataloggers. Meteorological stations and their associated tipping bucket gauges were monitored by Campbell Scientific CR10 dataloggers. Precipitation from a separate grid of 10 tipping bucket gauges on a 3 km by 5 km spacing on the east side of the Sevilleta was monitored using dataloggers designed by NMIMT. These dataloggers monitor a single channel and record the day and time of each individual tip. Data was collected from these dataloggers via a portable PC (Fig. 7). A Trimble Global Positioning System established accurate locations for all gauges. These positions are accurate to at least 10 m in both horizontal and vertical planes. As with the lightning data, all meteorological data were archived in the SIMS database.

Pecos

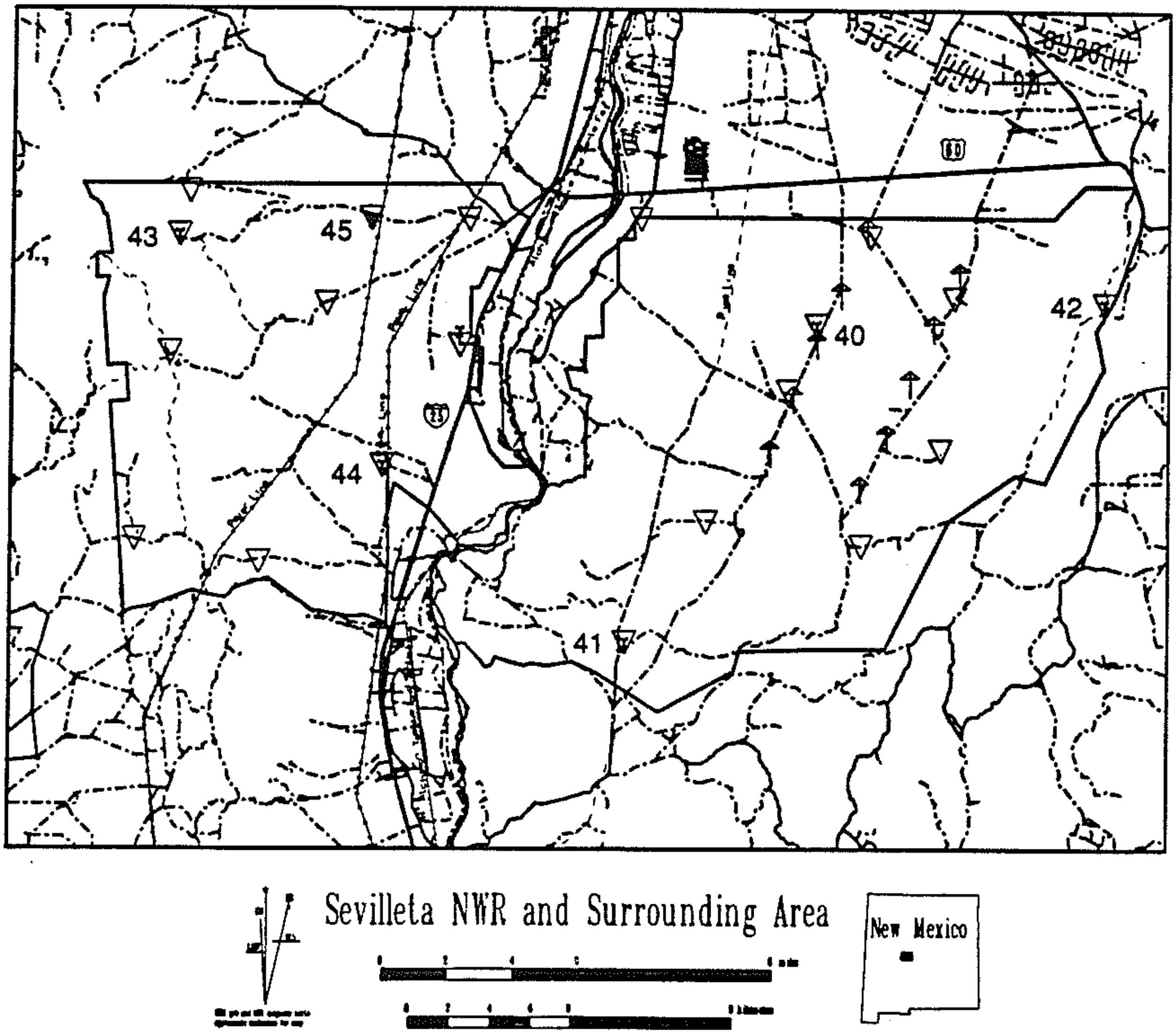
Precipitation data for stations within the Pecos watershed were extracted from "NOAA Climatological Data" bulletins. Table 2 lists the 34 stations used along with the June through September precipitation for these stations for 1989-91 as well as the long-term means. Two factors made this data more difficult to handle: 1) data were not immediately available (4 - 5 month lag time); and 2) the daily data reported covered a 24-hour period that was not uniform for all stations and was seldom the midnight to midnight period for which the lightning data was processed. To reduce these time disparities, monthly totals of precipitation and lightning attributes were used in developing algorithms for this watershed.

Hydrologic Modeling

General

Mathematical models which describe/simulate hydrologic processes have existed for over 200 years. Some of this century's more famous models are the empirically based Horton equation (1933) [see also Gardner and Widtsoe (1921)], the Stanford Watershed Model (Crawford and Lindsley 1966) and the SCS-Curve Number (CN) Method (e.g., McCuen 1982). Computers have permitted the development of models which more finely define hydrologic processes, spatial scales, and temporal steps. Still, all hydrologic models must process inputs to arrive at a desired output. For watershed modeling, a desired model result is a streamflow hydrograph (particularly peak rate and volume) which is processed from an initial precipitation input. In the case of single event models, the input is rainfall depth and duration. Specifically, rainfall must be divided into time incremental depths so that rainfall rate can be compared with potential infiltration. The difference between rainfall rate and infiltration rate becomes the runoff rate.

At any point, rainfall is variable with time. Even more daunting is the variability of rainfall with location, that is, spatial variability. Because of this spatial variability, most sophisticated hydrologic single event rainfall-runoff models incorporate a distributed



LTER Meteorological Stations

Code	Name
40	Deep Well
41	South Gate
42	Cerro Montoso
43	Red Tank
44	Rio Salado
45	Bronco Well

Gauge Symbols	
⊤	Meteorological Station
▽	Precipitation Chemistry Funnel
↑	Lightning Rain Gauge

Figure 6. Precipitation gauge network established for the Sevilleta Long-Term Ecological Research Project. Meteorological stations are coded as 40 - 45.

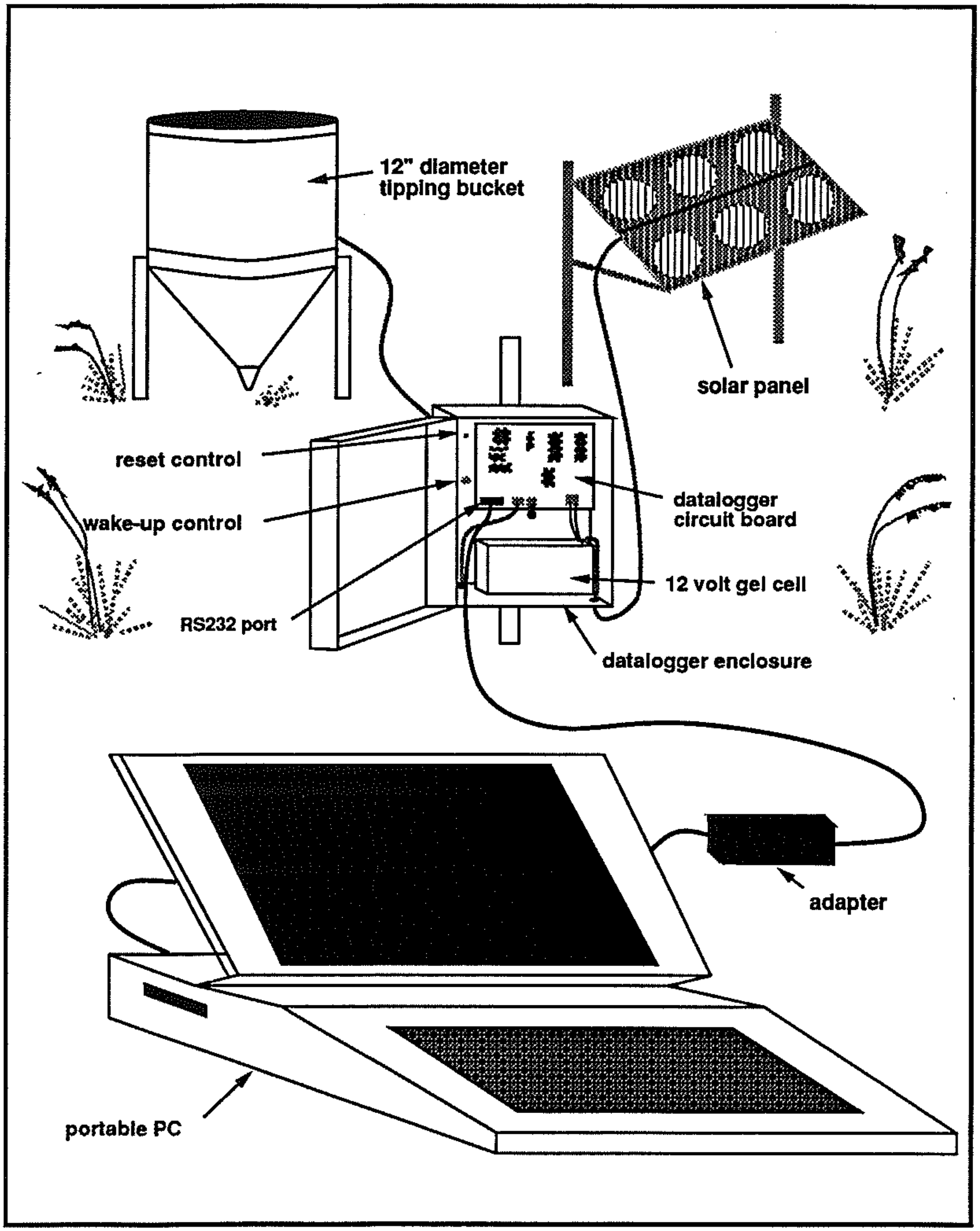


Figure 7. Tipping bucket gauge and datalogger (designed and constructed by NMIMT for LTER) used to monitor spatial and temporal variability of precipitation.

Table 2. Meteorological stations within the Pecos watershed with elevation, June - September precipitation and long-term (1951-1980) mean precipitation.

Station	Code	Elevation (feet)	Precipitation in mm (June - Sept.) 1989	1990	1991	1951-80 Average
Artesia	ART	3320	164	146	388	160
Bitter Lake	BLK	3664	240	142	348	178
Brantley Dam	BRD	3213	127	241	234	
Carlsbad Airport	CAA	3235	171	255	419	164
Carlsbad Caverns	CAC	4406	211	193	334	
Canton	CAN	4056	238	212	607	212
Capitan	CAP	6477	232	358	320	
Carlsbad	CAR	3120	95	175	437	178
Circle F Ranch	CFR	5400	256	350	256	
Clines Corners	CLC	6926	192	283	306	
Cloudcroft	CLD	8661	548	428	535	
Corona	CRN	6503	200	198	252	
Dilia	DIL	5200	189	163	301	203
Elk	ELK	5729	267	231	428	257
Fort Sumner	FSM	4026	223	229	533	205
Glorietta	GLO	7520	215	292	417	224
Hope	HOP	4100	202	155	275	
House	HSE	4853	213	206	439	227
Jal	JAL	3060	201	288	253	166
Las Vegas Airport	LVA	6868	170	299	277	244
Las Vegas	LVS	6349	172	334	310	
Mountain Park	MTP	6785	283	324	395	281
Ochoa	OCH	3460	163	205	134	123
Pecos Ranger Stn.	PEC	6940	92	277	442	225
Picacho	PIC	5044	244	410	283	
Pearl	PRL	3800	192	280	382	206
Ragland	RAG	5062	293	301	473	256
Ramon	RAM	5327	182	215	264	
Ruidoso	RDS	6937	395	435	324	
Roswell	ROS	3649	112	100	397	157
Sumner Lake	SML	4306	163	223	386	
Western AG	WAG	3520	165	194	361	
WIPP	WIP	3418	199	287	314	
Yeso	YES	4849	179	216	270	205

parameter approach. With this approach, the watershed can be subdivided into smaller areas usually based on some topographic/physiographic characteristic. Within these areas, rainfall depths and duration, soil properties, and vegetation characteristics are assumed spatially homogeneous.

A common practice is to assume that point rainfall is applicable to an area of about 26-square kilometers. However, this is usually not justified in the southwest as evidenced by Osborn (1983) who showed a rapid decrease in rainfall depth as area increased. His work was conducted on the Walnut Gulch experimental watershed in Southeast Arizona which has a dense (95 gages/175 square kilometer) network of rain gauges. For many upland watersheds, there can be a significant change of vegetation, soil, and land use over a 26-square kilometer area. Therefore, subdividing a watershed into smaller areas for modeling is a logical and preferred practice (Leavesley et.al. 1983, Riggins et. al. 1989, and Lopes and Lane 1990).

Subdividing the watershed makes it necessary to assign a rainfall depth and duration to each area. Uniformity could be assumed for the entire watershed, but as the watershed gets larger in area, such an assumption becomes inapplicable. The problem is: How can a realistic rainfall record (hyetograph) be assigned to a specific area in the watershed? Traditional techniques are available for translating depths at gauged points to points or areas in the watershed. Thiessen polygons or reciprocal- distance weighing schemes are two such techniques (Chow et.al. 1988 and Jones 1983 for examples). However, such techniques do not preserve the temporal resolution of the rainfall. The challenge is to overcome the spatial and temporal problems in defining rainfall for a poorly gauged watershed.

In the Southwest, almost all rainfall-runoff events are associated with thunderstorms although not all thunderstorms produce watershed runoff. Associated with the thunderstorm is lightning which strikes the ground and can be detected. The relationship between strikes and precipitation provided by William Rison, NMIMT, to the watershed modeling team was that 22,000 to 50,000 cubic meters (m^3) of precipitation was associated with each strike. If each strike had a 2 km location error associated with it, the volume should be distributed over a 4 km^2 area. Therefore, one (1) strike in a 4 km^2 area would produce 12.5 mm of precipitation depth for a 50,000 m^3 volume. This number formed the basis for estimating rainfall from lightning strike data.

Description of Target Watershed and Events

Four USGS gauged watersheds were selected for study; Foster Canyon near Continental Divide, Sixmile Canyon near Fort Wingate, Eagle Creek below South Ford near Alto, and Mogollon Creek near Cliff (See Figure 8 and Table 3). These watersheds range in area from 20 km^2 to 180 km^2 and were chosen because they represent typical topographic conditions and vegetation types that exist in New Mexico. None of them has a rain gauge or other meteorological instrumentation in the basin.

Each watershed was delineated on a 7.5 minute quadrangle topographic map and divided into 2 km by 2 km grids or blocks. These 4 km^2 blocks corresponded to the area over which the rainfall volume associated with each lightning strike was distributed.

Average daily discharges and instantaneous peak discharge data were obtained for each watershed for water-years 1987 through 1990 from the USGS Water Resources Data Publications, except for Eagle Creek which was not active in 1987. For each watershed, six of the larger runoff events occurring during thunderstorm season (June-Sept.) were selected and the corresponding water-stage recorder data were requested from the appropriate USGS field office. Lightning strike data for the areas in and around each watershed were supplied by William Rison and were compared temporally and spatially to the selected runoff events. Those events for which no water-stage recorder data were available, for which no lightning data were

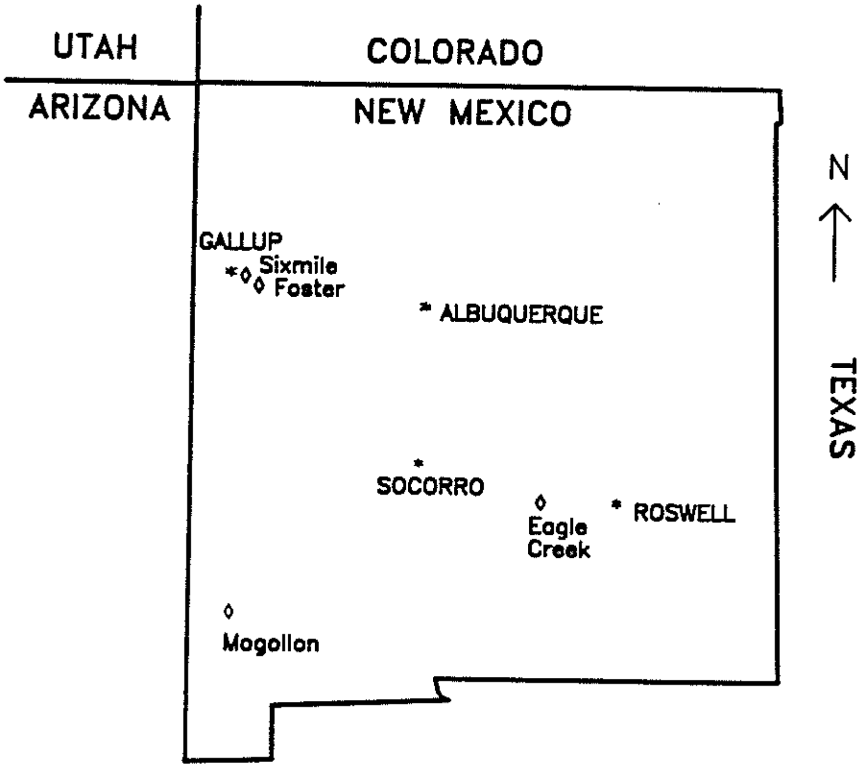


Figure 8. Locations of watershed hydrologic modeling study sites.

TABLE 3. DESCRIPTION OF WATERSHEDS STUDIED

Name	*Gage Location*	*Elevation, m*	*Area, km^2*
Foster Canyon near Continental Divide	R14W., T14N., Sec.18 Continental Divide 7.5 minute quadrangle, NW1/4, SW1/4	2160	43.5
Sixmile Canyon near Ft. Wingate	R15W., T15N., Sec.31 Ciniza 7.5 minute quadrangle, SE1/4, SE1/4	2110	27.7
Eagle Creek below S. Fork near Alto	R13E., T10S., Sec.31 Angus 7.5 minute quadrangle, SW1/4, SE1/4	2320	21.1
Mogollon Creek near Cliff	R18W., T13S., Sec.13 Rice Ranch 7.5 minute quadrangle, SE1/4, SE1/4	1660	179

available, or for which there was no lightning activity preceeding the runoff were not analyzed further. Table 4 lists the events studied in each of the four watersheds.

In analyzing each event, the lightning strikes were located on the topographic map and assigned to the appropriate 2 km by 2 km block. Each strike was assumed to have occurred in the center of the block and the corresponding rainfall to have been distributed equally over the 4 km^2 area. In calculating the equivalent rainfall depth and equivalent runoff depth, only that part of the watershed contained in the blocks which received the strikes was considered to be contributing runoff.

TABLE 4. EVENTS STUDIED

Date	Est. Contributing Area, km^2	Peak Flow (cms)	Volume, m^3	Equiv. Depth Runoff, mm
Foster Canyon near Continental Divide - 43.5 km ^{2}				
8/24/88	7.2	1.60	22,400	3.1
8/30/88	3.6	2.78	22,640	6.3
8/31/88	4.0	3.71	22,490	5.6
7/10/90	26.7	1.90	15,000	0.6
8/14/90	6.8	2.32	15,200	2.3
Sixmile Canyon near Fort Wingate - 27.7 km ^{2}				
8/06/88	8.2	10.87	44,300	5.4
8/25/88	2.4	3.48	15,000	6.3
7/26/88	8.9	1.36	5950	0.7
Eagle Creek below South Fork near Alto - 21.1 km ^{2}				
7/17/88	2.6	1.08	27,680	10.7
8/04/88	11.1	1.36	22,280	2.0
8/19/88-8/20/88	5.2	1.36	149,400	28.7
9/1/88	11.2	1.49	58,140	5.2
7/21/89-7/22/89	16.6	0.74	20,840	1.3
Mogollon Creek near Cliff - 179 km^2				
7/28/87-7/31/87	61.5	6.22	550,780	8.9
7/13/88-7/17/88	48.8	9.27	76,100	1.6
8/14/88-8/16/88	111.8	6.12	807,100	7.2

RESULTS AND DISCUSSION

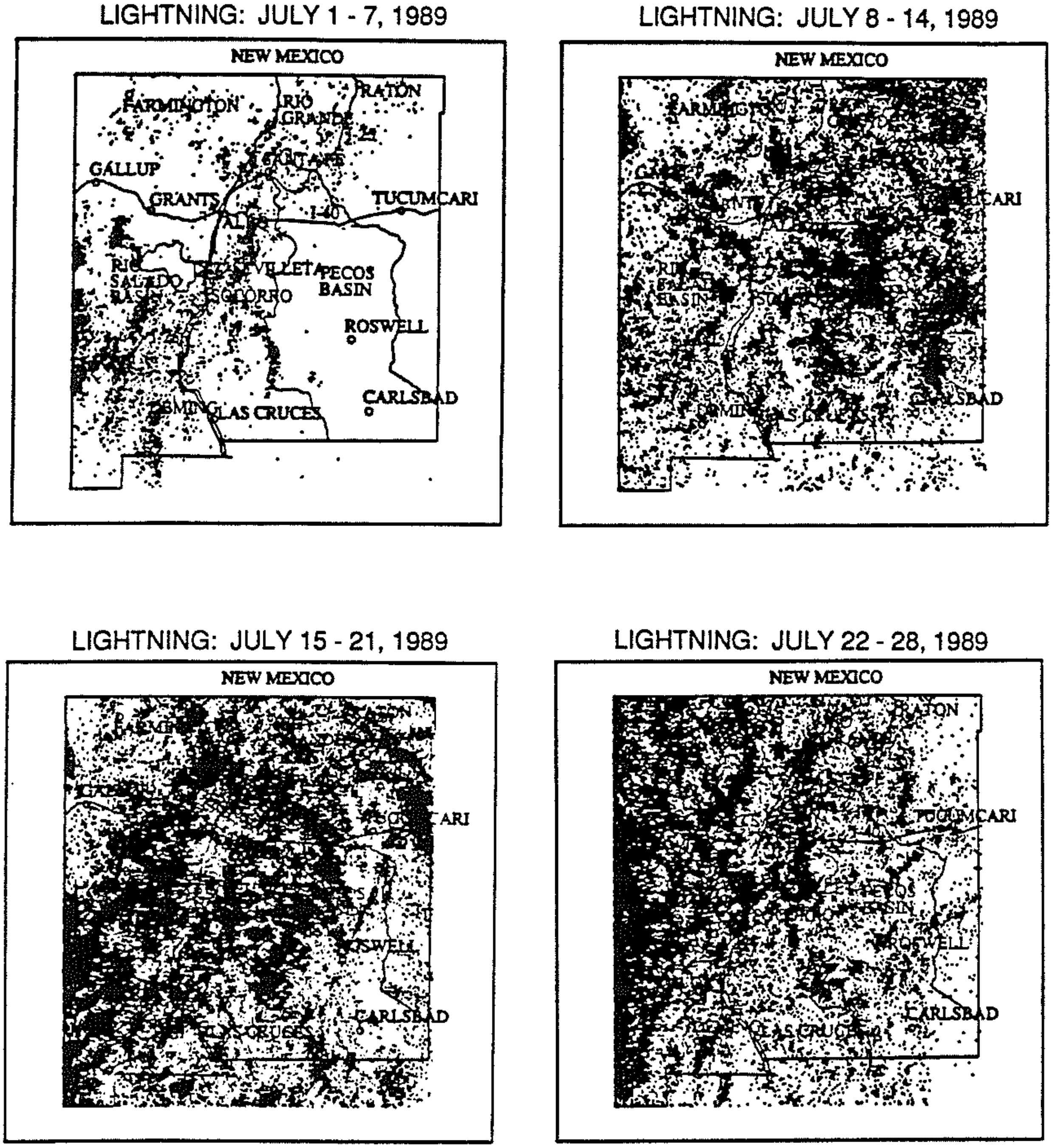
General

Several points should be made regarding the lightning data. First, these lightning data represent only the cloud-to-ground strikes which represent only one-fourth the total number of lightning strikes (Prentice and Mackerras 1977). We are unable to identify the proportion of the rain produced by cloud-to-ground strikes. Therefore, volume per strike reported is on average using only 25% of the actual total number of lightning strikes. Second, the nominal accuracy of the DF system is reportedly 2 km. However, a grass fire that started on the Sevilleta in 1989 with no closely associated lightning strikes detected by the DF system made us question this accuracy. A request for visual reports of locations and times of lightning strikes revealed that, while a person may have claimed to have come "close" to being struck by lightning, the DF data often showed no lightning strikes in their proximity. While the slight inaccuracy in the reporting time makes it difficult to establish exactly where the DF system might have actually located the strike, generally the best guess was more on the order of 3 to 8 km away from the eye-witness location. While these visual reports represent an extremely small sample size, it still suggests real uncertainty in lightning location. Third, while lightning location and precipitation data are collected for the entire year, we will focus on the period from June 1 to September 30 as this is the period of highest convective thunderstorm and, consequently, lightning activity. The localized nature of these thunderstorms makes this the period of highest spatial variation in precipitation inputs. During the other months, precipitation over the entire Sevilleta was much less variable on a per-storm basis. During this four month convective storm period, there also can be storms or periods of precipitation that are frontal and have little or no lightning associated with them. These storms are most prevalent during late August and September. The other extreme is represented by convective storms in June that often have "dry lightning" associated with them in which precipitation may be generated by a thunderstorm cell but little or none of the resulting precipitation reaches the ground due to evaporation as it passes through a very dry atmosphere that is typical during this period.

Lightning

The number of lightning strikes in New Mexico for 1989 was lower than for 1990 and 1991. Figure 9 shows the pattern of lightning strikes during a typical "monsoon season" in New Mexico. Each figure shows a week of lightning strikes during July 1989. During week 1, the lightning (and presumably precipitation) is restricted mostly to higher elevation regions. By the second week, moisture carried north by the Bermuda high from the Gulf of Mexico appears to have moved up into eastern New Mexico. In the two subsequent weeks this moisture continues to move north and west.

Lightning on the Sevilleta is restricted generally to the months of May through September with July, August and September having the greatest lightning frequency (Fig 10A). Figures 11 - 13 show the monthly pattern of lightning strikes for each of the 3 years. Table 5 shows the monthly lightning strike totals for these years.



LIGHTNING: JULY 1 - 7, 1989

LIGHTNING: JULY 8 - 14, 1989

LIGHTNING: JULY 15 - 21, 1989

LIGHTNING: JULY 22 - 28, 1989

Figure 9. Lightning strikes in New Mexico during the first four weeks of July, 1989 depicting onset of "monsoon" season.

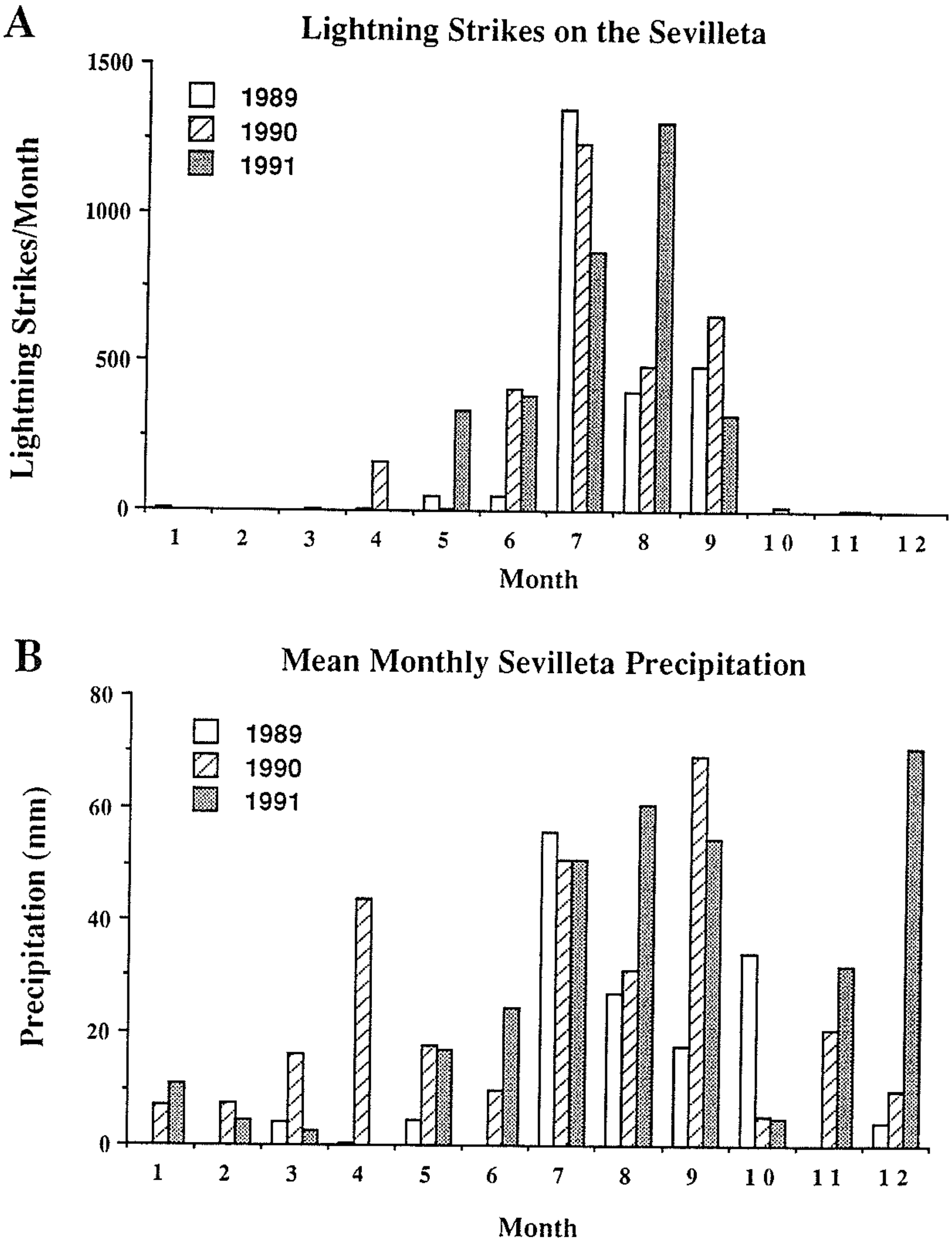


Figure 10. Monthly (A) lightning strike totals and (B) mean precipitation for the Sevilleta National Wildlife Refuge for 1989 - 1991. Lightning strikes occurred in the rectangular boundary the researchers used for the refuge (see Fig. 2).

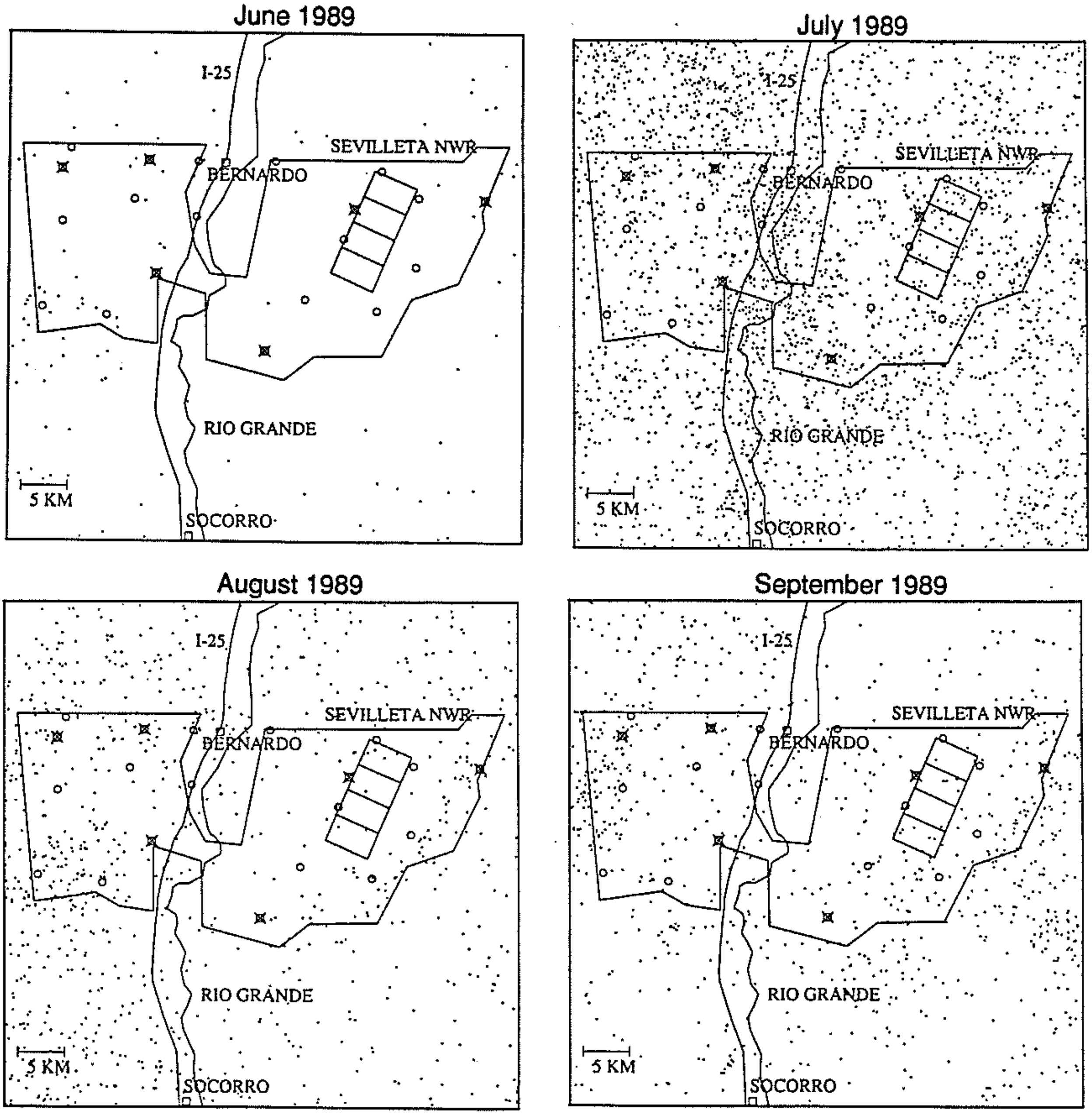
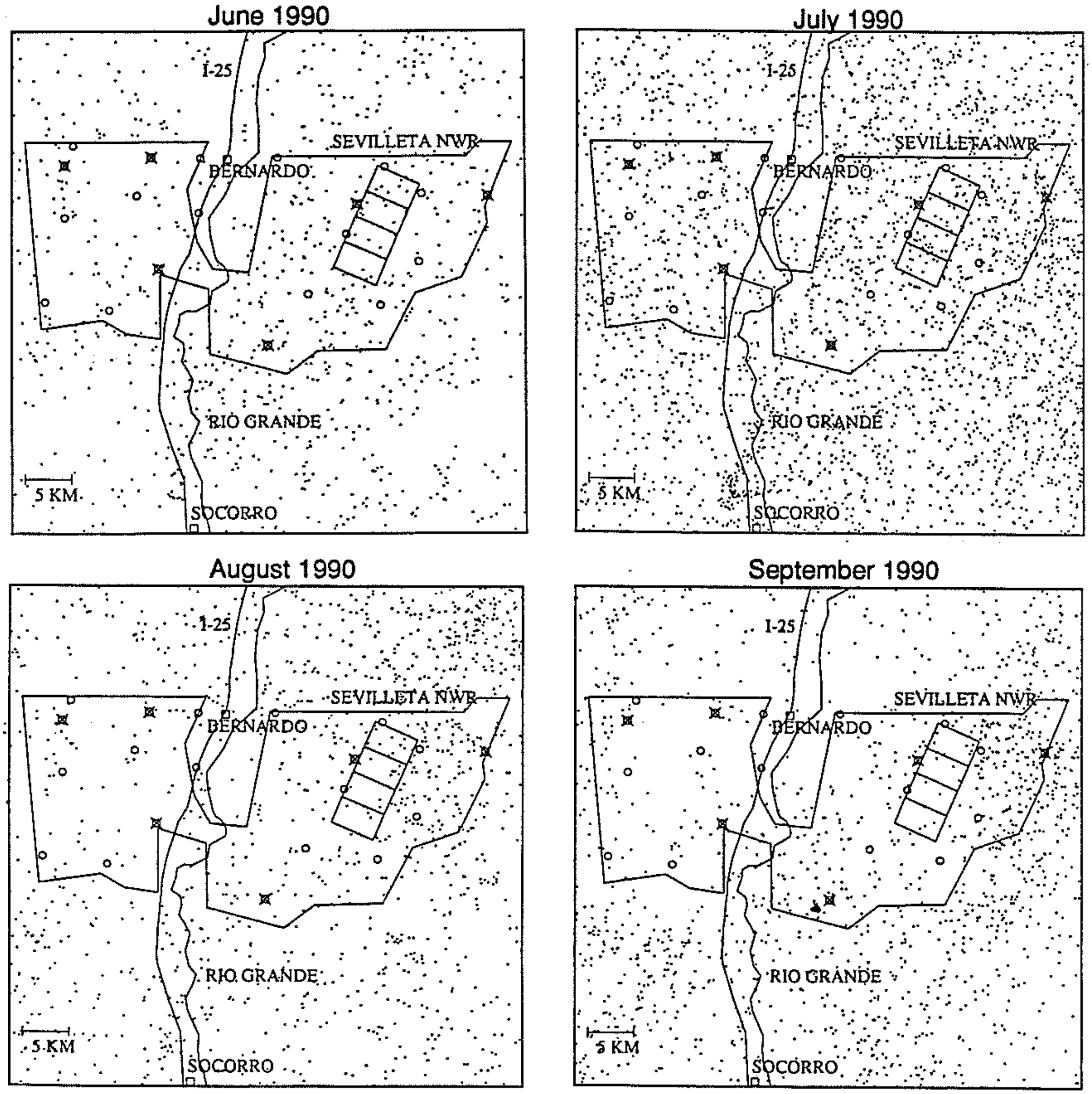


Figure 11. Monthly lightning strikes on the Sevilleta National Wildlife Refuge for June through September, 1989.



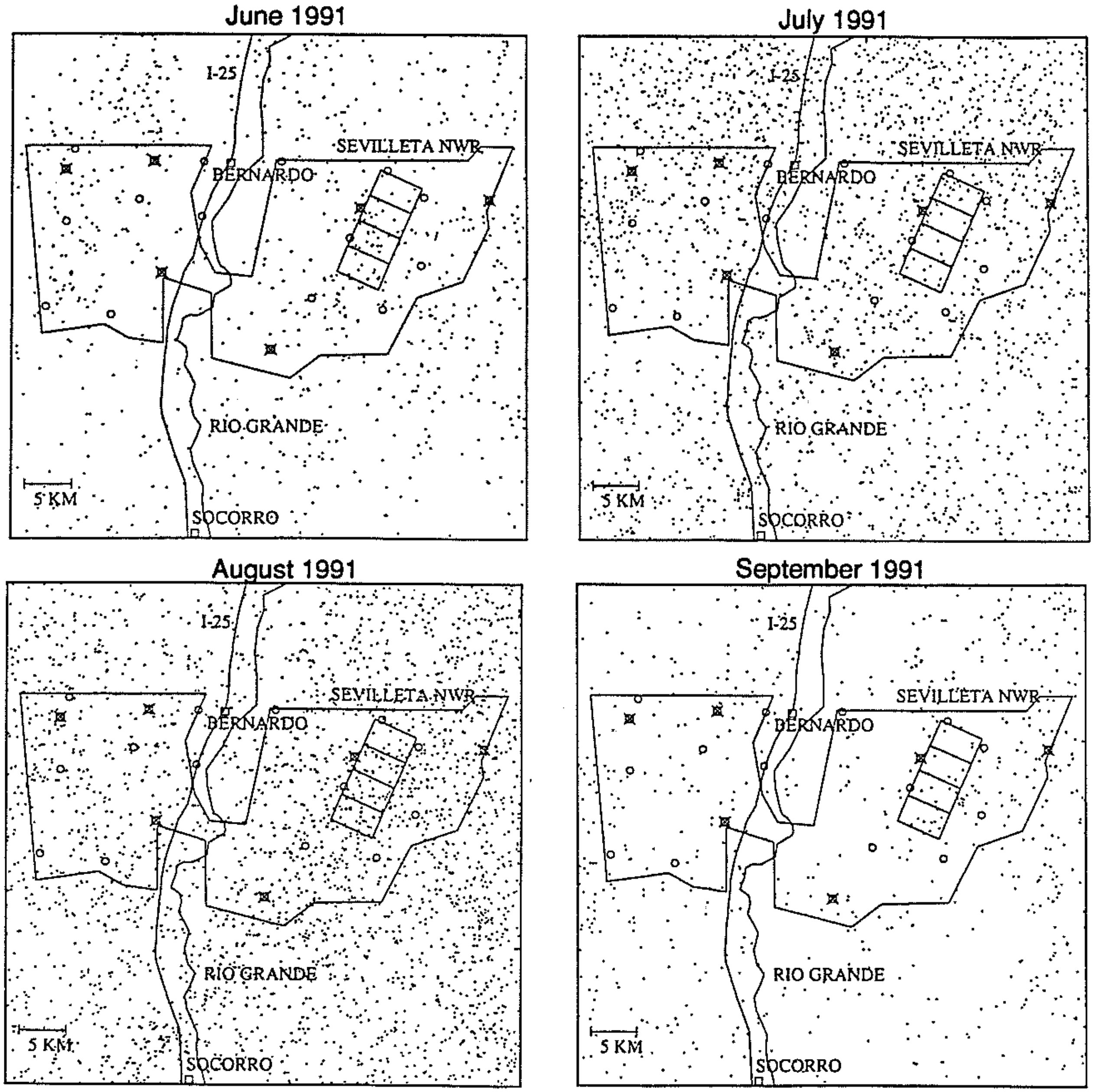
June 1990

July 1990

August 1990

September 1990

Figure 12. Monthly lightning strikes on the Sevilleta National Wildlife Refuge for June through September, 1990.



June 1991

July 1991

August 1991

September 1991

Figure 13. Monthly lightning strikes on the Sevilleta National Wildlife Refuge for June through September, 1991.

Table 5. Monthly lightning strikes on the Sevilleta National Wildlife Refuge for 1989 - 1991 as determined by ARC/INFO.

Month	1989	1990	1991
Jun	26	278	271
Jul	843	769	461
Aug	258	305	840
Sep	288	370	202

Precipitation

Sevilleta

As with lightning, precipitation for 1989 was lowest with 1990 and 1991 following in ascending order. Differences in precipitation during the June - September periods of those years parallelled the yearly differences. However, each of these three years had a quite different precipitation pattern (Fig 10B). In 1989, the winter and spring months were dry, a typical pattern for this region. June was virtually devoid of precipitation with the summer "monsoons" not beginning until mid to late July. August and September were at or below normal (as defined by the 1951 -1980 averages for Socorro) and after one significant storm in early October, no precipitation fell until late December resulting in a year with 70% of normal precipitation. In 1990, the winter months were normally dry, but considerable moisture in late March, April, and early May brought the year to well above normal. June, July and August were normal and September was above normal. October, November and December were normal resulting in total annual precipitation being 130% of normal. In 1991, the year again started out below normal with a very dry March, April (no precipitation) and early May. A storm in mid-May brought the cumulative total back to normal. Unusually heavy June precipitation, especially in certain areas, coupled with above average precipitation in July, August and September produced a very wet summer. A very wet November and December produced precipitation totals that were 150% of normal.

Pecos

The Pecos watershed covers a large latitudinal and elevational range so that the trends in precipitation were more difficult to generalize. Table 2 lists the June through September precipitation totals for the 34 gauges in the Pecos watershed. Long-term means (1951-80) are listed for those stations that had them. For both 1989 and 1990, most stations had near-normal precipitation while for 1991 all of the stations with records received precipitation well in excess of average. In many cases this excess was at least 100% above normal. Figure 14 shows the long-term trends for both the Pecos (using those stations with long-term means) and Sevilleta (a mean of the Socorro and Bernardo stations). While the normal monsoon trend holds for both areas, on average the Pecos stations receive considerably more precipitation during all of the summer months as well as for the year. Both sites receive 60% of their precipitation during the June through September period.

Precipitation Prediction

The use of lightning strikes to predict precipitation comes down to a question of scale (both temporal and spatial). We would like to develop algorithms that would be applicable over the broadest temporal and spatial scales possible. At the same time, a very desirable aspect of the remote lightning data would be to predict precipitation at the smallest scale possible (again both temporally and spatially). Since convective storms can drop large quantities of precipitation on quite small areas during a very short time while areas within only a few kilometers remain virtually dry, remotely locating lightning and predicting rain volumes is a very attractive technology. However, reality demonstrates the difficult nature of our work.

First, the location of all lightning-producing precipitation (both cloud-to-cloud and cloud-to-ground) would need to be available. Working with only 25% of the data (only cloud-to-ground) is a definite handicap. Second, the accuracy of the lightning location system, even if the nominal 2 km accuracy were a fact, makes prediction for small areas susceptible to considerable errors. The accuracy of many strikes is in excess of 3 km. Third, the rain falling from rapidly moving and wind-blown convective cells makes the chances unlikely that precipitation generated by a given strike will reach the ground directly below that strike. While the lightning strike is mapped as a single point on a plot, the produced rain looks like a smear, which we are trying to analyze using gauges of relatively minute cross sectional area. Fourth, the atmospheric and meteorological conditions change daily as well as seasonally so that frontal storms and dry-lightning storms work to cancel each other when trying to develop broad temporal regressions. Even year-to-year variations in lightning-generated precipitation may be greater than currently thought. Fifth, the accuracy of precipitation gauges is susceptible to the vagaries of such things as wind, precipitation type (e.g. hail which tends to bounce out of most gauges), and precipitation intensity when tipping bucket gauges can get swamped by very intense precipitation. In spite of these difficulties, the results reported below are very promising for certain areas and scales.

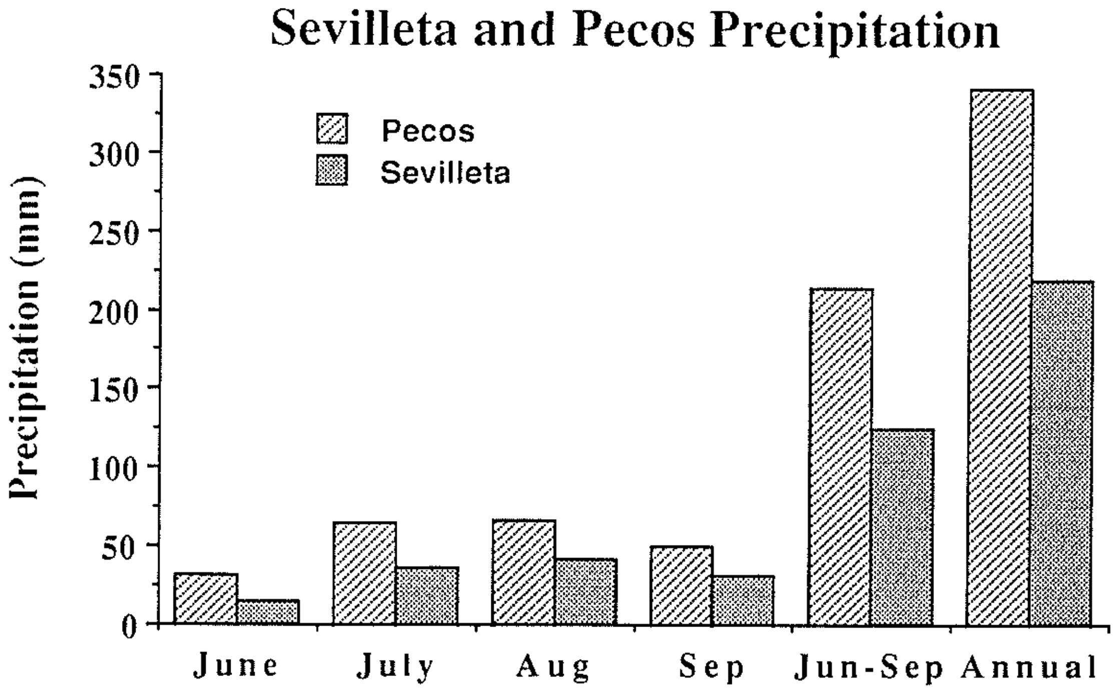


Figure 14. Comparison of long-term mean precipitation for the Pecos Basin and the Sevilleta. Pecos values come from the mean of 19 long-term values in Table 2 and Sevilleta values are based on the mean from the Bernardo and Socorro stations.

Sevilleta

As a first step in developing precipitation predicting algorithms, correlations were run on precipitation versus the various lightning variables. For 1989 and 1990 buffers of radii 1, 2, 3, 5, and 10 km were applied to each of the meteorological stations. Correlations of daily precipitation at those stations were run against 1) number of lightning strikes, 2) number of lightning return strokes, and 3) field strength. Overall, the highest correlations were found for lightning strikes within buffers having a 3 km radius. Simple linear regressions using such a 3 km buffer provided the following equations for calculating precipitation depth per day in mm:

1989 Precip. = 1.42 * strikes + .27 r2=.525 (1a)
1990 Precip. = 1.31 * strikes + .54 r2=.395 (1b)
1991 Precip. = 1.13 * strikes + .74 r2=.176 (1c)
Overall Precip. = 1.28 * strikes + .53 r2=.307 (1d)

While all of these regressions were highly significant (p<.0001) for all years, the percentage of the error explained by lightning strikes (r^2) alone was only 53%, at best. In fact, for 1991 the r^2 was less than 0.2. The intercept was found to be significantly different than zero in every case. This is presumably a function of the influence of non-convective precipitation. However, in most cases, no lightning strikes within 3 km of a station corresponds with no precipitation at that station.

Using the slopes of equations 1a - 1d, and assuming that all of the precipitation from the strikes within the 3 km buffer fell within that buffer, the average precipitation per cloud-to-ground lightning strike for the 3 years and overall period of study calculates to 40,149, 37,039, 31,950 and 36,190 m^3, respectively. This is greater than that reported by other studies (Pipegrass et al. 1982) but within the range Rison reported.

Cognizant of all the factors mentioned in the previous section, we tried to find other variables affecting precipitation inputs. Because antecedent atmospheric conditions can influence precipitation quantity, meteorological variables such as temperature and humidity that were available for each station were added to a stepwise multiple regression. Elevation was also added to the stepwise regression.

While the primary factor was still lightning strikes, a second regressor, mean relative humidity - R. H. (minimum relative humidity in 1989) increased the r^2 significantly for all years. Below are the annual and overall regressions for daily precipitation using lightning strikes and relative humidity.

1989 Precip. = 1.36 * strikes + .0588 * min. R.H. -.887 r2=.617 (2a)
1990 Precip. = 1.22 * strikes + .0396 * R.H. -.96 r2=.454 (2b)
1991 Precip. = 1.00 * strikes + .0518 * R.H. -1.57 r2=.224 (2c)
Overall Precip. = 1.17 * strikes + .0423 * R.H. -1.17 r2=.357 (2d)

The use of relative humidity results in better prediction for a number of reasons. First, during the dry month of June, lightning strikeduring conditions of low relative humidity may result in no precipitation. The dry atmosphere causes the rain to evaporate before reaching the ground. This is a period when there is significant soil warming needed for convective storms but the atmospheric moisture is too low to allow a consistent relationship between lightning and moisture reaching the ground. Second, high relative humidity in the early autumn months (i.e., cooler and increased frontal storms) results in predictions of higher precipitation volume for a given number of lightning strikes. Third, while elevation did not fall out as a significant regressor, it is correlated with relative humidity. Lower temperatures at higher elevation result in higher relative humidity despite identical specific humidities. Consequently, more precipitation will be predicted for higher elevation sites than for lower elevation sites even if lightning strikes are identical.

Finally, elevated relative humidity associated with purely frontal storms will result in predicting some precipitation for such storms while regressions with lightning strikes as the sole regressor will always predict none. On the negative side this also results in predicting precipitation for days following storms when relative humidity often remains high but there is no precipitation.

Figures 15A and 15B show measured and predicted precipitation for two typical meteorological stations for 1990 using equation 2d. This shows the disparity between measured and predicted precipitation. However, the method's value is in whether it can predict precipitation amounts better than gauges some distance from that area and whether it be done without having to visit the gauge. Figure 15C shows the measured precipitation for the 2 stations in 15A and 15B, which are located about 15 km apart. A correlation between the rainfall depths collected by the two stations gave an r of .19, while correlation coefficients between lightning-predicted and measured precipitation for the Deep Well and Cerro Montoso stations were .40 and .82, respectively. Day 249 points out the extreme spatial varibility that is common with convective storms. This was an extreme case and for some stations the correlations between stations were much better. A negative aspect to using relative humidity in a predictive regression is the almost total lack of mean relative humidity records for remote areas. Relative humidity data taken from the NOAA Climatological Bulletins include only a single daily reading.

On a localized spatial scale, predictability of lightning on a monthly basis was better than that on a daily basis. Regressions of monthly station precipitation totals (in mm) against total strikes within a 3 km radius gave the following regressions:

1989 $\text{Precip.} = 1.725 * \text{strikes} + 6.23$ $r^2=.764$ (3a)
1990 $\text{Precip.} = 1.961 * \text{strikes} + 14.83$ $r^2=.499$ (3b)
1991 $\text{Precip.} = 1.266 * \text{strikes} + 34.64$ $r^2=.148$ (3c)
Overall $\text{Precip.} = 1.738 * \text{strikes} + 18.34$ $r^2=.390$ (3d)

For 1991, the monthly regression was actually poorer than the daily. However, as with the daily data, a second regressor of relative humidity increased the r^2 considerably.

1989 $\text{Precip.} = 1.488 * \text{strikes} + 1.35 * \text{R.H.} - 16.13$ $r^2=.844$ (4a)
1990 $\text{Precip.} = 1.31 * \text{strikes} + 1.06 * \text{R.H.} - 19.52$ $r^2=.780$ (4b)
1991 $\text{Precip.} = 0.62 * \text{strikes} + 2.06 * \text{R.H.} - 13.18$ $r^2=.740$ (4c)
Overall $\text{Precip.} = 1.112 * \text{strikes} + 1.06 * \text{R.H.} - 19.51$ $r^2=.771$ (4d)

Using Equation 4d, figures 16A and 16B show predicted and measured precipitation for the Deep Well and Cerro Montoso meteorological stations for the three years .

For larger spatial scales, it is possible to develop regressions for entire areas such as the Sevilleta or a watershed basin. Using the GIS-produced data, daily lightning strikes can be regressed against the average daily precipitation values. At this point, the ability of the small network of precipitation gauges to predict the average precipitation for the entire Sevilleta is brought into question. Using only lightning variables, the best regression for the Sevilleta as a

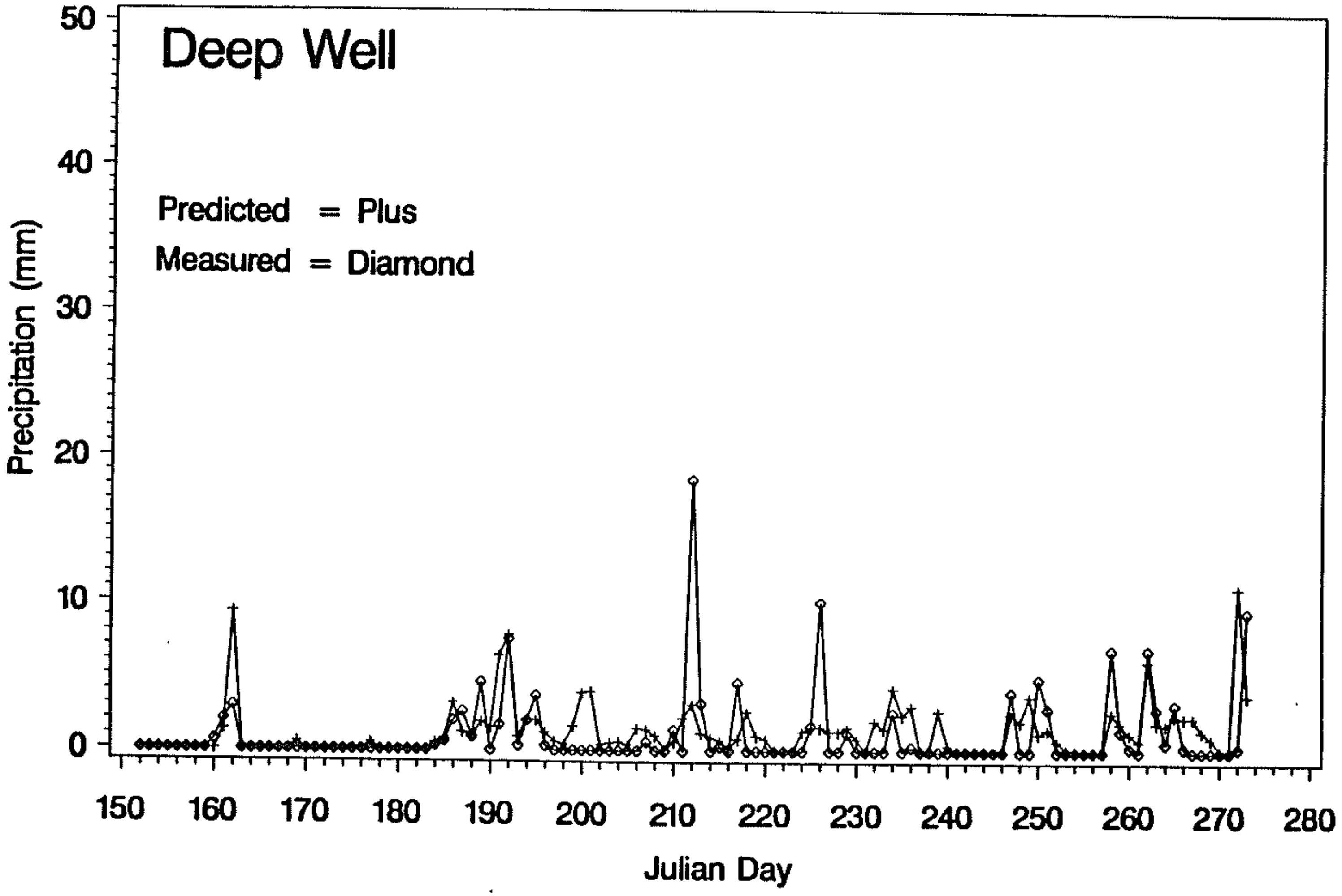


Figure 15A. Daily measured and predicted precipitation at Deep Well during June - September, 1990. Julian Day 152 = June 1 and Day 273 = September 30.

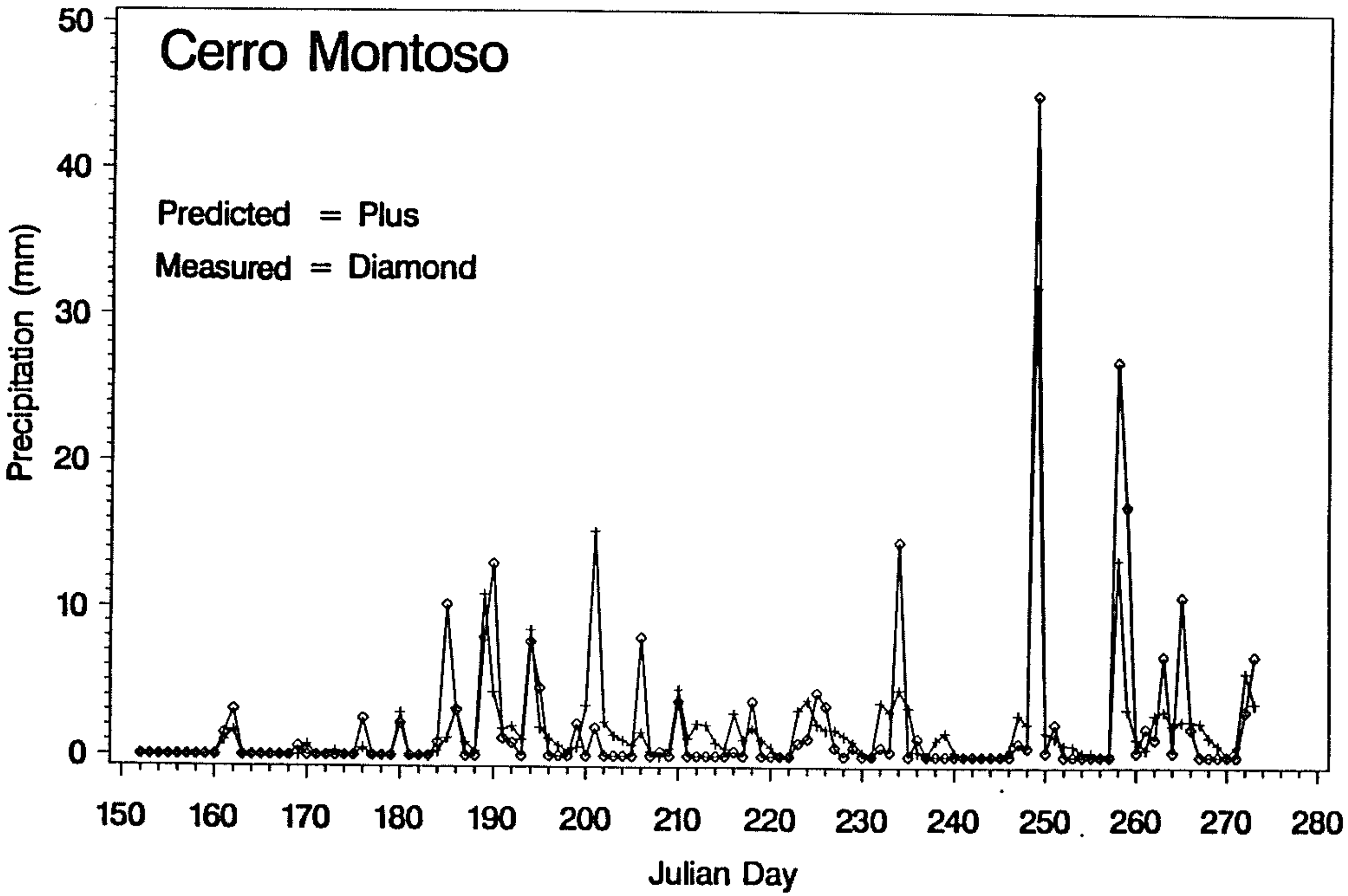


Figure 15B. Daily measured and predicted precipitation at Cerro Montoso during June - September, 1990. Julian Day 152 = June 1 and Day 273 = September 30.

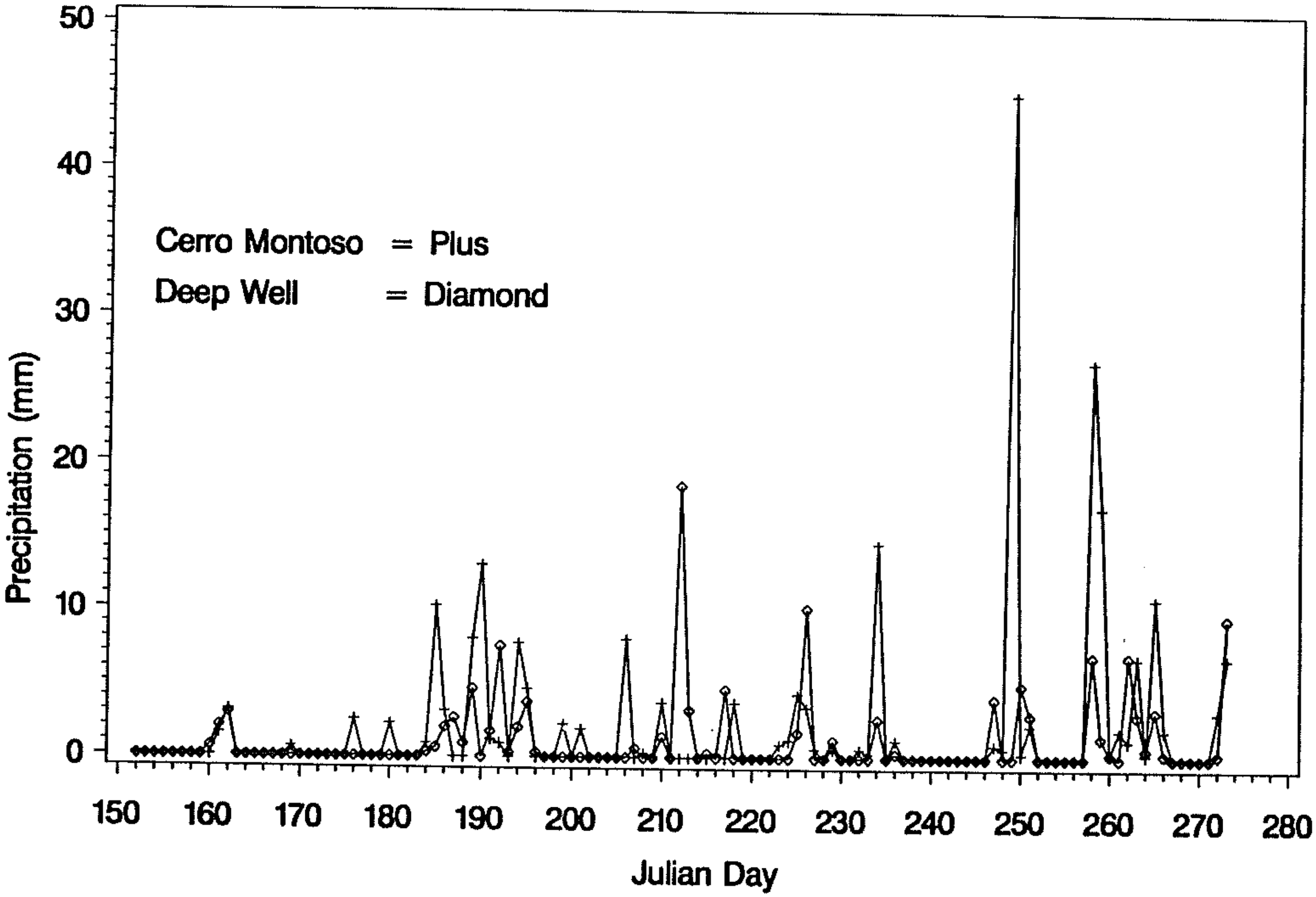


Figure 15C. Daily measured precipitation at Deep Well and Cerro Montoso during June - September, 1990. Julian Day 152 = June1 and day 273 = September 30.

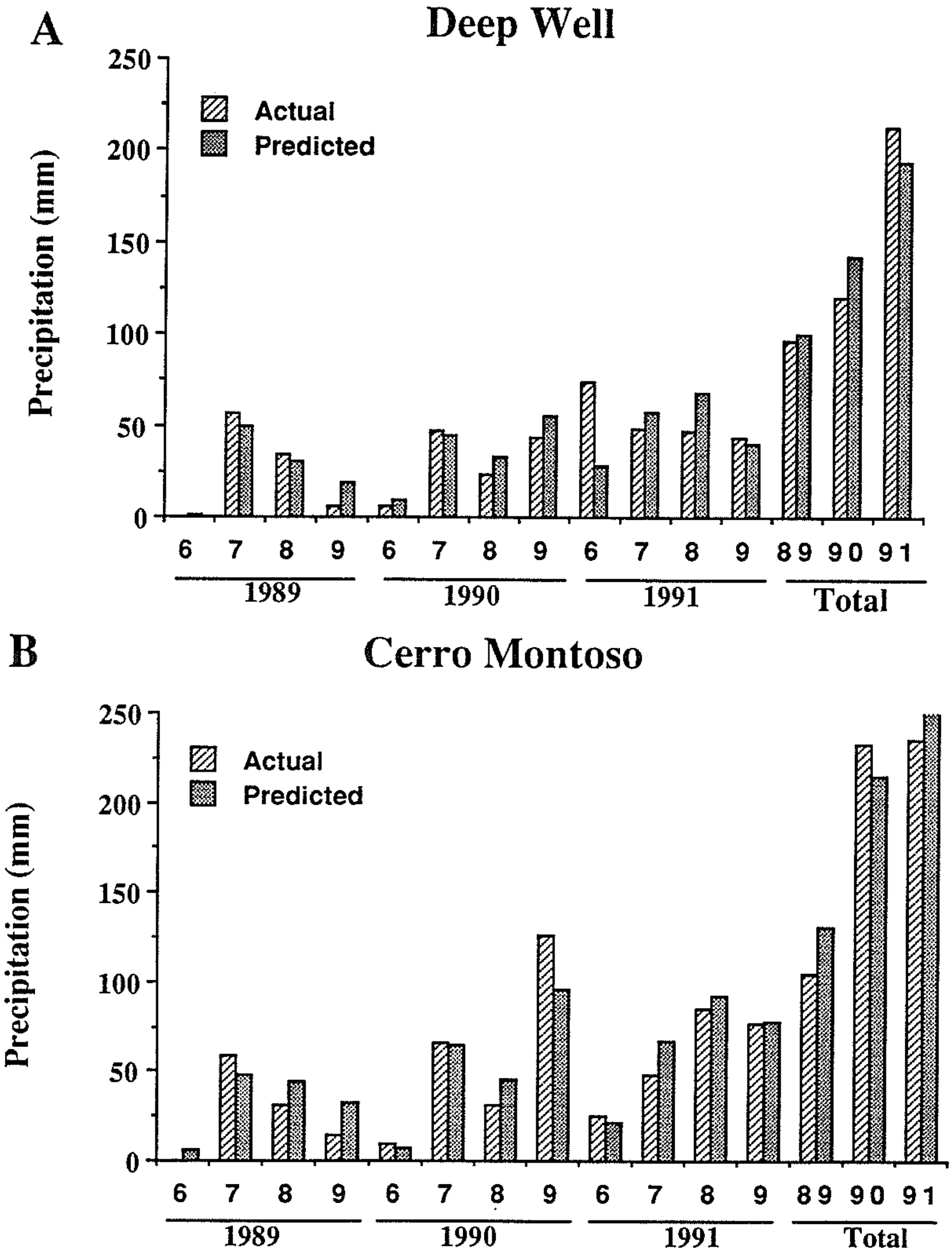


Figure 16. Monthly predicted and actual precipitation for meteorological stations at (A) Deep Well and (B) Cerro Montoso for June - September, 1989 through 1991.

whole used total monthly return strokes.

$$\text{Precip} = .01889 * \text{Return Strokes} + 16.82 \qquad r^2 = .437 \qquad (5)$$

Using this regression, predicted precipitation for the four months of each year is plotted with measured precipitation in figure 17. Again, a measure of atmospheric moisture improves predictability, particularly in June and September. In this case the average relative humidity (a mean from all the stations) is found to be the primary regressor with strikes contributing another 10% to the variability explanation.

$$\text{Precip.} = 1.242 \text{ R.H.} + .02878 * \text{strikes} - 25.16 \qquad r2 = .829 \qquad (6)$$

Figure 17 shows how this improves the prediction.

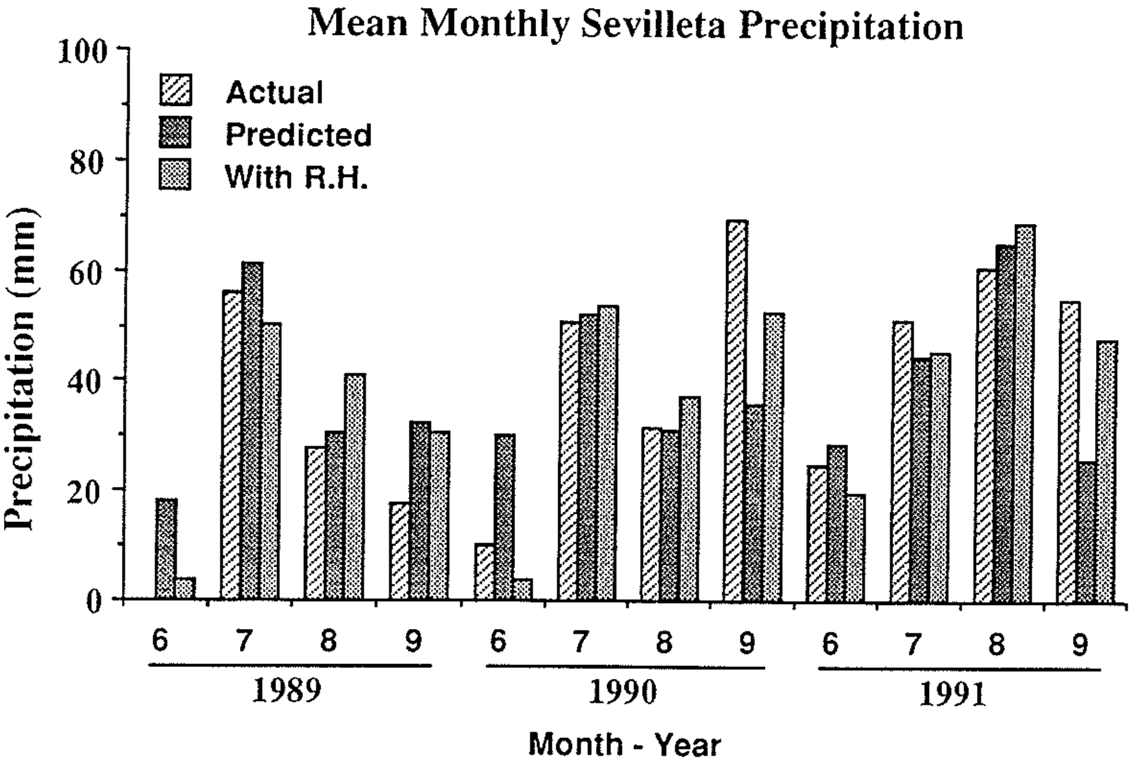


Figure 17. Measured and predicted mean Sevilleta precipitation for 1989 through 1991.

GIS permits another means of calculating predicted precipitation for given areas of the Sevilleta using the lightning strikes and humidity as predictors. Placing a relatively fine grid over the entire Sevilleta (Fig. 18, 2 km between points), we used the buffering C program to count the number of strikes within 3 km of each corner point. This count was then passed to our regression, equation 4d, to calculate the predicted precipitation for each point. These precipitation amounts for all points on the grid then became an INFO database. This was passed to an ARC/INFO package which allowed the contouring of the predicted precipitation. Figures 19A and 19B show this contouring for two months in 1991.

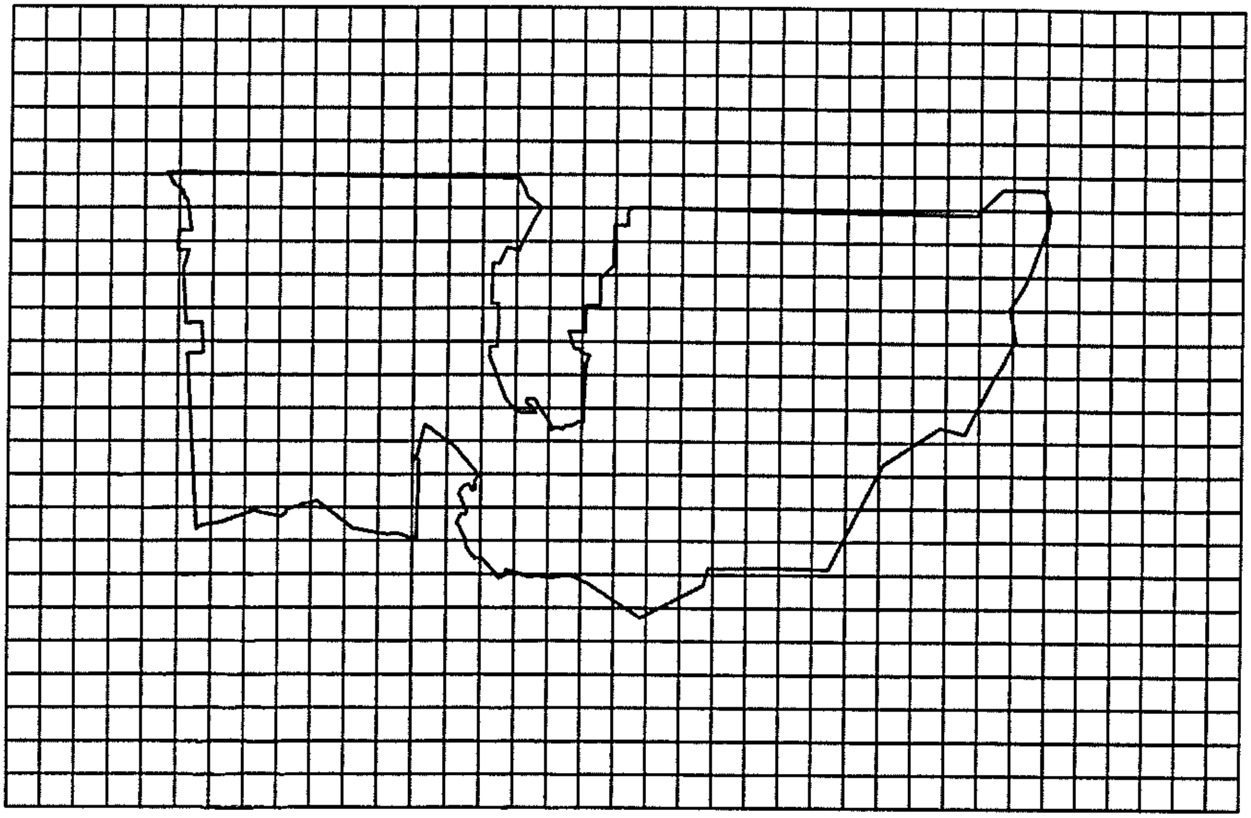


Figure 18. Grid (2km x 2km) overlaid on Sevilleta and surrounding areas. Corner points were used to develop coverage of precipitation for the refuge.

Pecos

Initial inspection shows a disparity between the precipitation and lightning strike data for the Pecos watershed. For the three years of the study, there appears to be an inverse correlation between the two (Table 6). While the precipitation totals increased in each successive year, the lightning displayed a reverse trend with the greatest number of lightning strikes in the driest year, 1989.

Table 6. Lightning strikes for the Pecos watershed for June - September. Precipitation is the average precipitation (mm) for the 34 stations in the Pecos watershed during the same period.

Year	Total Lightning Strikes	Average Precipitation
1989	121,799	211
1990	109,731	253
1991	101,702	364

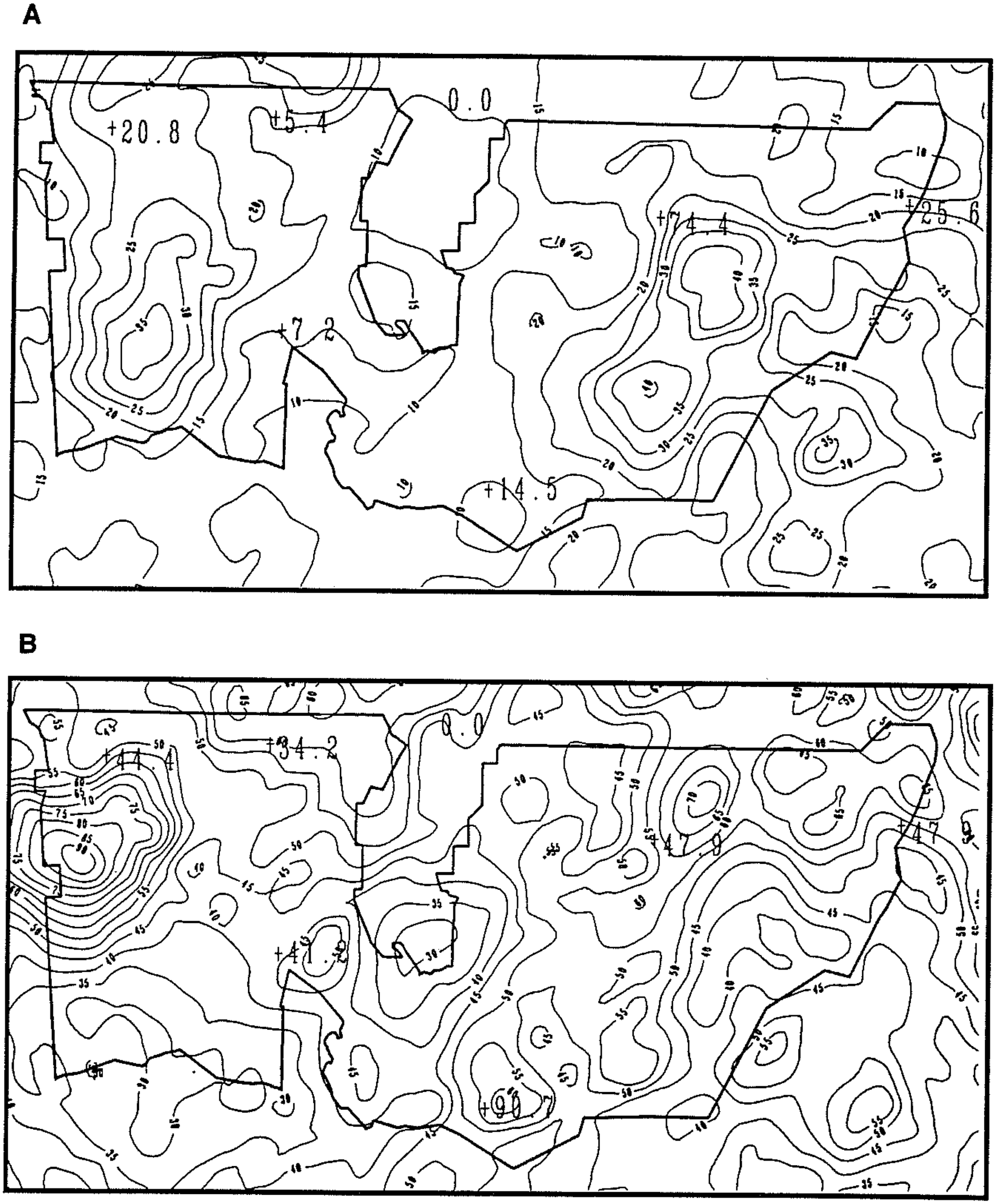


Figure 19. Monthly precipitation contours (mm) as mapped by ARC/INFO using lightning strikes and mean monthly relative humidity for (A) June, and (B) July, 1991. Actual values for meteorological stations are also shown.

However, for all three years there is a significant correlation ($P<.0001$) between precipitation and lightning strikes within a 3 km radius around the 34 stations. Linear regressions predicting depth of precipitation (in mm) per month for the individual three years and the three years overall were as follows:

1989	Precip. = 2.24 * strikes + 23.92	$r^2 = .276$	(7a)
1990	Precip. = 1.91 * strikes + 40.69	$r^2 = .268$	(7b)
1991	Precip. = 2.09 * strikes + 67.51	$r^2 =.109$	(7c)
Overall	Precip. = 1.97 * strikes + 45.43	$r^2 = .168$	(7d)

While the slopes are quite similar for all three years, the intercepts are quite different. This suggests that there were quite different ratios of convective to frontal type precipitation for the three years in this watershed. This would explain the overall inverse correlation between the total strikes and total precipitation. The summer months of 1991 had the greatest frontal precipitation while those of 1989 had the least. These frontal storms may be the cause of decreased convective activity because of their cooling effect on the surface over large surface areas. The lack of relative humidity readings for the stations prevented us from adding this variable to a stepwise regression to help explain some of the variability as we did with the Sevilleta data. While elevation was identified as significant in the stepwise regression for each of the three years, it added little to the r^2 and was not significant in the overall equation. An analysis of only the September data at all 34 stations demonstrated no significant regressors with precipitation. Using only the June - August data resulted in the linear regressions predicting monthly precipitation depths as follows:

1989	Precip. = 2.29 * strikes + 26.11	$r^2 = .270$	(8a)
1990	Precip. = 2.13 * strikes + 30.64	$r^2 = .373$	(8b)
1991	Precip. = 2.37 * strikes + 58.60	$r^2 = .147$	(8c)
Overall	Precip. = 2.19 * strikes + 39.50	$r^2 = .223$	(8d)

The lack of any measure of atmospheric moisture (humidity) is unfortunate because the watershed, being such a large area, includes a much larger range of both elevation and latitude meaning that the role of humidity is more complex. Also, this area is subject to more frontal storms from the northwest than is the Sevilleta and that reduces the magnitude of precipitation from convective storms with lightning. The area between the Pecos watershed and the Sevilleta is a transition zone between the storm tracks passing to the north and the band of moisture that is transported up from the Gulf of Mexico in the summer.

Hydrologic Modeling Methods

The runoff and sediment yield model, ARMSED (Riggins et.al. 1989) was initially selected to model the watershed. ARMSED, however, requires a temporally discrete precipitation input (hyetograph). The time resolution of the strike data was not sufficient to derive a hyetograph for each event. Information was received from William Rison on the Sevilleta NWR rain-gauge network. This information was used in an attempt to resolve some of the spatial and temporal problems that were encountered and to investigate the volume/strike values. The data were not sufficient to resolve the temporal variability problem. Therefore, it was decided to adopt a rainfall to runoff depth approach, the Soil Conservation Service Curve Number Method (SCS-CN).

After reviewing the characteristics of each watershed, a CN of 65 was assigned (woodland area, soil group B) globally. The actual curve number used for each event was adjusted, up or down, according to the antecedent moisture condition. The strike data were located on the appropriate 4 km^2 block. In calculating equivalent rainfall depth, the volume/strike value was proportioned by the percentage of the watershed contained in the block and converted to an equivalent depth. The SCS-CN procedure was applied and runoff depth was calculated.

For example, if a particular block on the edge of the grid system was 60% filled by part of the watershed and received two lightning strikes during a particular storm, then, using 50,000 m^3/strike, 0.6 of 100,000 m^3 or 60,000 m^3 of precipitation was assumed to have fallen on 0.6 of 4 km^2 or 2.4 km^2 of contributing surface area. This would yield an equivalent rainfall depth of 25 mm. With a CN of 81 and a rainfall depth of 25 mm, a runoff depth of 2.3 mm would result. Over an area of 2.4 km^2, the 2.3 mm of runoff depth would result in a volume of 5520 m^3 of runoff from that particular block. The runoff from all the blocks would be summed to yield a predicted runoff volume. The total runoff volume was converted to an equivalent depth and compared to the equivalent measured runoff depth as reported from the USGS gauges.

After using the described method on the first two watersheds studied, Foster Canyon near Continental Divide and Sixmile Canyon near Ft. Wingate, it was discovered that rainfall volumes of 22,000-50,000 cubic meters/strike were too small to account for the measured runoffs. Using Foster Canyon and Sixmile Canyon for calibration, a larger volume/strike value was derived. This value was then tested on Eagle Creek and Mogollon Creek.

Using the eight events from Foster Canyon and Sixmile Canyon and working backward through the SCS-CN procedure, (i.e., using the measured runoff depth to calculate the rainfall depth) it was apparent that a value of 160,000 m^3 per strike was reasonable for these watersheds (see Table 7). When this value was used on the test watersheds, Eagle Creek and Mogollon Creek, the results were not as consistent, however. Table 8 shows a comparison of runoff depths as measured from the USGS gauges versus the runoff depths as predicted from the lightning strike/CN procedure with 160,000 m^3 per strike. Table 9 shows the measured versus predicted runoff information, including the predicted runoff values generated by using plus and minus one standard deviation (20,000 m^3) from the 160,000 m^3/strike value.

Other possible ways of analyzing the data were explored. It was evident that there was large spatial variability using 4 km^2 blocks. The modeling procedure was modified to take the variability into account but led to little change in results. Temporal distribution of lightning within a particular event was studied in the hope of temporally distributing rainfall within the event. In most cases, the small number of strikes per event did not lend itself to this type of analysis. Increasing the number of events studied may help in validating the results. However, the selected watersheds were very typical of most hydrologic modeling situations and therefore represented an adequate test of the methodology.

TABLE 7. EVENTS AT FOSTER CANYON AND SIX MILE CANYON

Date	*Est. Contributing Area, km^2*	*Equivalent Depth Runoff (mm)*	*Estimated Curve Number*	*Calculated Volume/strike m^3*
Foster Canyon				
8/24/88	7.2	3.1	72	172,400
8/30/88	3.6	6.3	81	153,000
8/31/88	4.0	5.6	81	147,000
7/10/90	26.7	0.6	55	148,100
8/14/90	6.8	2.3	65	204,000
Sixmile Canyon				
8/6/88	8.2	5.4	81	143,000
8/25/88	2.4	6.3	81	150,000
7/26/89	8.9	0.7	65	163,000

TABLE 8. EAGLE CREEK AND MOGOLLON CREEK EVENTS
Comparing Predicted and Actual Runoff, Q/strike = 160,000 m^3

Date	*Est. Contributing Area, km^2*	*Estimated Curve Number*	*Predicted Runoff mm*	*Measured Runoff mm*
Eagle Creek, Area = 21.1 km^2				
7/17/88	2.6	81	7.4	10.6
8/4/88	11.1	81	7.4	2.0
8/19/88-8/20/88	5.2	81	7.4	28.7
9/1/88	11.2	75	3.6	5.2
7/21/89	16.6	75	3.6	1.3
Mogollon Creek, Area = 179 km^2				
7/28/87-7/31/87	61.5	75	4.6	8.9
7/13/88-7/17/88	48.8	81	17.0	1.6
8/14/88-8/16/88	111.8	75	26.7	7.2

TABLE 9. MEASURED AND PREDICTED RUNOFF DEPTHS
± One Standard Deviation

Eagle Creek

Date	*Measured Runoff Depth mm*	*Predicted Runoff Depth mm*	*+1 Standard Deviation mm*	*-1 Standard Deviation mm*
7/17/88	10.7	7.4	10.2	4.8
8/4/88	2.0	7.4	10.2	4.8
8/19/88-8/20/88	28.7	7.4	10.2	4.8
9/1/88	5.2	3.6	5.2	2.0
7/21/89	1.3	3.6	5.2	2.0
Mogollon Creek				
7/28/87-7/31/87	9.0	4.3	6.4	2.8
7/13/88-7/17/88	1.6	17.0	22.6	11.9
8/14/88-8/16/88	7.2	26.7	35.8	21.8

SUMMARY

Despite some described limitations, the use of remote lightning location as a means of predicting precipitation depths remains a promising technology. In the Southwest, where precipitation is a precious commodity, the ability to prognosticate the movement of water through the hydrologic cycle can have widespread applications. With the predictions of global climate change, the ability to monitor climatic parameters such as temperature and moisture are paramount in monitoring any biotic responses that these changes might precipitate. The Sevilleta National Wildlife Refuge has been deemed an ideal spot to monitor any such changes as it is located at the junction of three distinct biomes, the Great Plains, the Great Basin and the Chihuahuan Desert. The LTER project initiated in 1989 by the University of New Mexico and funded by the National Science Foundation is attempting to detect and monitor short-term climatological changes and any biotic responses to such changes to help predict and assess the consequences of any long-term climatic changes.

While this study is in its infancy, the short-term climatic variable that shows the greatest variability from the norm is precipitation, both seasonal and annual. Quantifying this variable is of primary concern to the LTER study. Therefore, among other things, this study has provided an excellent opportunity to test and refine this technology for the benefit of both USGS and NSF. Numerous tools and programs were developed to quantify and predict precipitation inputs at various temporal and spatial scales. These will continue to be refined and expanded as studies in the Sevilleta continue.

We have found that the remote lightning location data are not entirely diagnostic on their own in predicting precipitation quantities and intensities under all conditions. However, with the aid of atmospheric moisture conditions, the data did provide generally good predictions of monthly precipitation totals during the convective storm period of June - September for the Sevilleta. On a daily basis, accurate analysis was not as good as that on a monthly basis, but was still often as good or better than that provided by precipitation gauges in relatively close proximity to the area of interest.

The major difficulties with the use of lightning data for hydrologic modeling in this preliminary study were that: 1) the temporal resolution of the data for this application was not amenable to discrete time-step modeling; 2) spatial inaccuracies of the strikes can render the modeling technique ineffective at the scales used in this study; and 3) the rainfall depth to lightning strike ratios reported in other studies did not work adequately for the tests.

The SCS-CN methods appeared to be the best way to relate runoff to rainfall when studying lightning/precipitation interactions. However, the variability of the data makes the procedure difficult to apply at this time. Continued refinement is needed regarding the appropriate temporal and spatial scales for successful hydrologic modeling and improved accuracy for algorithms using associated meteorologic data that filters non- lightning/precipitation phenomena.

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