FINAL REPORT

CLOUD SEEDING OPERATIONS AND EVALUATIONS FOR THE SAN ANGELO RAIN ENHANCEMENT PROGRAM DURING THE PERIOD 15 APRIL - 15 OCTOBER 1989 WITH ADDITIONAL INFORMATION ON THE 1985-1988 SEASONS

Prepared For

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San Angelo, Texas

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EXECUTIVE SUMMARY

This Final Report presents a summary of the San Angelo Rain Enhancement Program conducted by Atmospherics Incorporated (AI) under contract with the City of San Angelo, Texas. The period of operations was 15 April through 15 October 1989, the fifth consecutive summer of cloud seeding sponsored by the City. The program's primary goal is replenishment of surface reservoirs providing the City's municipal water supply and, secondarily, increased precipitation over residential areas to reduce demand for municipal water. It was recognized that increased rainfall would also benefit the farming and ranching communities.

AI came to Texas prepared to assess and seed a broad range of cloud situations using techniques tailored to each event's characteristics. This overall capability included a variety of sensing and seeding systems and modes, allowing application of radar-coordinated airborne seeding technology appropriate to both the static and dynamic seeding concepts. Major equipment systems provided to the program included a full computerized satellite-downlink weather data acquisition system, a weather radar with aircraft tracking capability, and a high performance twin-engine seeding aircraft.

This report summarizes AI's 1989 seeding operations, describes the rainfall across the region, and presents preliminary results of ongoing evaluations of the seeding results, including the prior seasons of operations from 1985 through 1988.

OPERATIONS - 1989

During the 1989 season, 64 flights totaling 132.4 hours were flown by the Cessna 421 seeding aircraft. Of these, 49 included actual silver iodide (AgI) treatment. On 28 flights the seeding was accomplished near the tops of developing cumulus clouds using ejectable pyrotechnic devices. On 15 flights the seeding was conducted at cloud base in the inflow/updraft areas using burn-in-place pyrotechnics attached to wing-mounted racks. Six flights involved both on-top and cloud base seeding, in response to changes in storm organization. Of the 49 seeding flights, 11 were initiated at night. The average duration of the seeding flights was 2.27 hours, with the average duration of the treatment period being 1.28 hours.

Seeding material usage during the 1989 season involved of a total of 1,892 silver iodide flare-type pyrotechnic devices, including 1,550 of the ejectable type and 342 burn-in-place. Since each device emits 20 grams (.70 ounces) of the silver iodide nucleating material as smoke particles, the total nucleant released was 37,840 grams (83.4 pounds).

RAINFALL - 1989

Rainfall during the 1989 project period was below normal across much of the southern High Plains, including Texas. This was true for the southern and western portions of the San Angelo target area. Even drier conditions prevailed south and west of the operational area. However, analysis of May through September raingage data shows wetter conditions over portions of the project target area from southwest of San Angelo extending northeastward and eastward then broadening into the extreme eastern portion of the target. Notably, the northeastern portion of the target area had rainfall amounts above seasonal normals. This pattern suggests a seeding signature over and spreading downwind from the priority portions of the San Angelo target area.

Although rain was reported somewhere in the San Angelo network on 60 of the 183 days of the program, a few heavy rain events accounted for a large proportion of the total rainfall, consistent with the local climatology. The rain frequency in 1989 was greatest in May, early June, and mid-July through early August, whereas rainfall was minimal in the latter half of June and August, and during most of September and October.

EVALUATION OF SEEDING EFFECTS

Assessment of the seeding effects made use of target-control regressions derived from official historical rainfall records. From monthly data for stations within the target and outside to the west and south, a 25-year base period before seeding from 1960 through 1984 was selected. Six control stations and nine target stations were used in the analysis, along the following steps.

- Linear regression relationships between target and control stations and target-control mean values were derived, using the 25-year base period rainfalls (May through September).
- The regression equations were then used to evaluate the five seasons' seeding operations, individually and collectively, by using the observed control area rainfall to predict each target station's rainfall and the overall target rainfall.
- The predicted rainfalls were compared with actual measured amounts during the seeded period to obtain estimates of the seeding effects.

The results of the analysis show all five seasons with apparent positive results. Seasonal increases ranged from 7% to 29%. The 1989 season value was +19%, slightly above the 5-year average of +18%. These values are in line with those published in capability statements of the Weather Modification Association and the American Meteorological Society.

Neither the individual season positive indications nor their absolute values carry strong statistical significance, due to the natural variability of summertime precipitation, but the serial occurrence of all five being positive is highly significant. Using the simple analogy of a coin toss, where the probability of a given outcome of each toss is 0.5 (50%), the probability of five consecutive seasons showing positive values is only 3%. Stated another way, the hypothesis that the seeding had no effect can be rejected with 97% confidence.

Further, the area closest to San Angelo and its reservoirs, where most of the seeding took place, had larger apparent seeding effects ranging from 28% to 43%. For that priority area the mean rainfall increases average between 3" and 5" per season (May-Sept).

Analysis of this project is continuing. Final results should be available by 31 December 1989. Once those results are available, interested parties will have quantitative information for use in objectively considering the future of the San Angelo cloud seeding program.

KEY FINDINGS - CONCLUSIONS

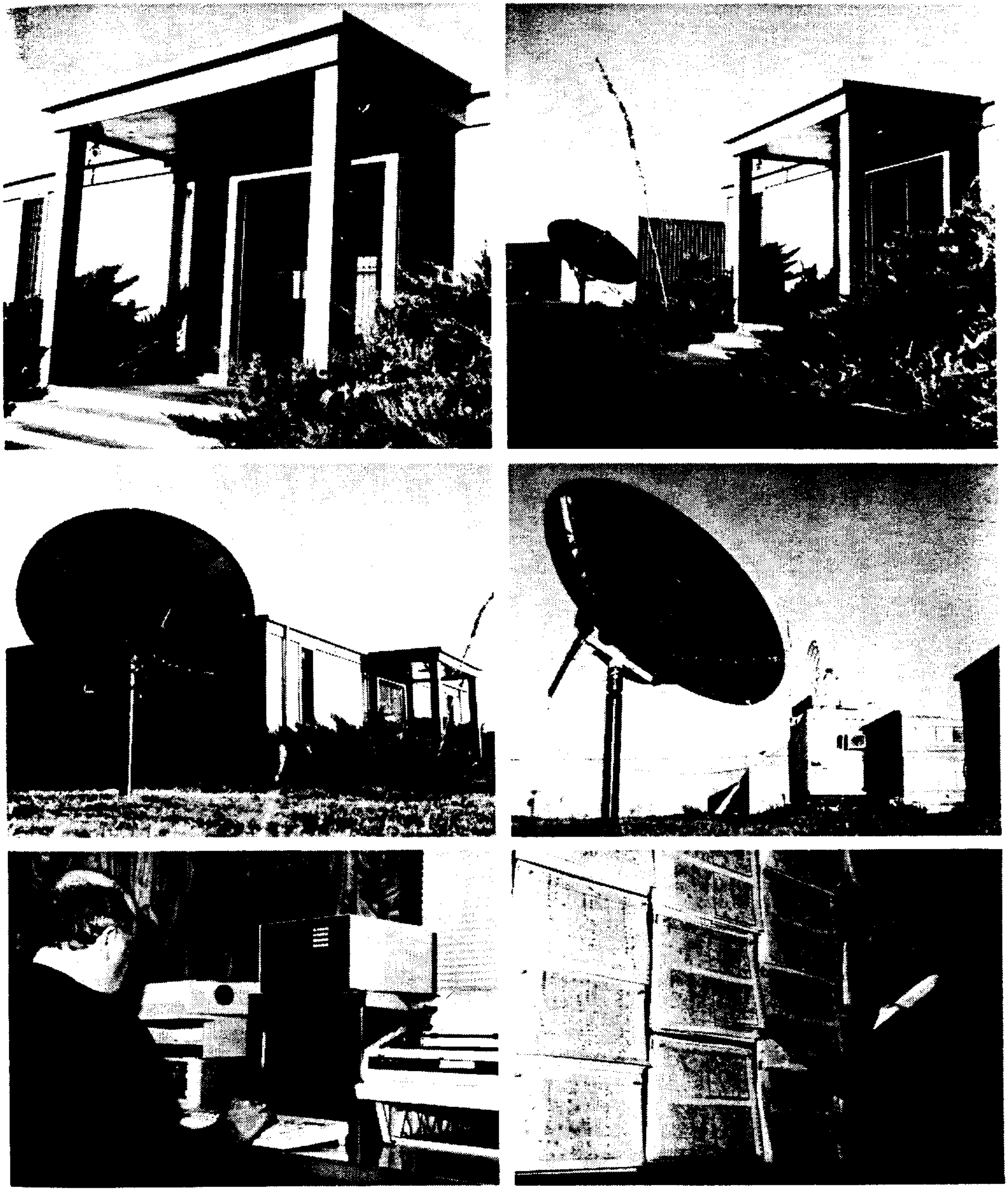
- Despite below normal rainfall across much of the southern High Plains, portions of the project area received above normal amounts during the 1989 operations, suggesting a seeding signature over and downwind of the priority portion of the target.

- The 1989 season's area-wide rainfall was 19% above what a statistical prediction method indicates would have occurred in the absence of seeding.

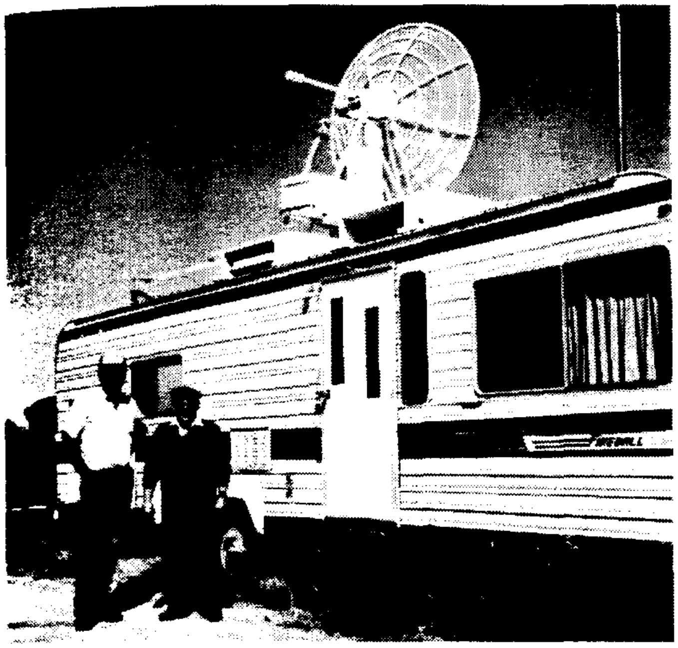
- Statistical evaluation shows all five seeded seasons (1985-1989) with apparent positive seeding effects. Seasonal area-wide rainfall increases ranged from +7% to +29%, with an overall project average of +18%.

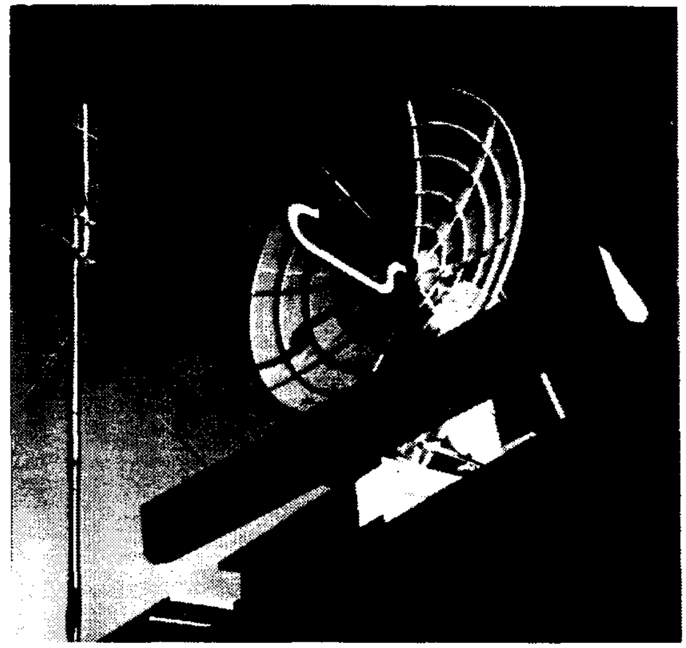
- The probability of five consecutive seasons showing positive values due to chance is 3%. Thus, the hypothesis that the seeding had no effect can be rejected with 97% confidence.

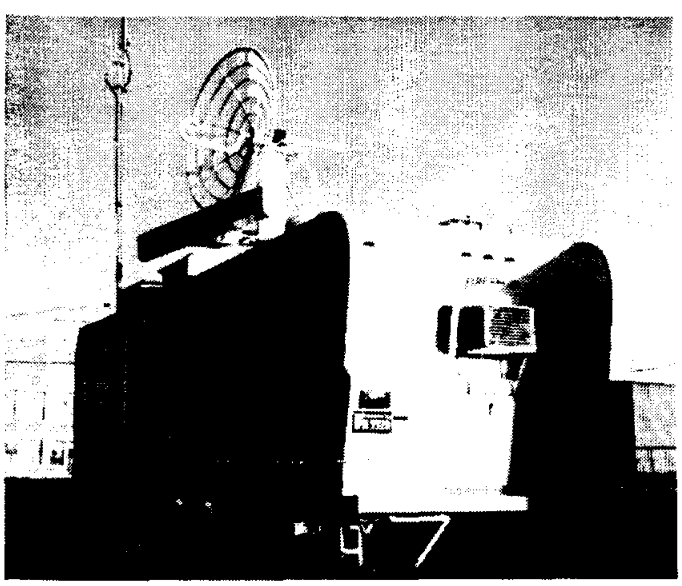
- The area nearest San Angelo and its reservoirs, where most of the seeding took place, showed overall rainfall increases of 28% to 43%, an additional 3" to 5" on average each season.



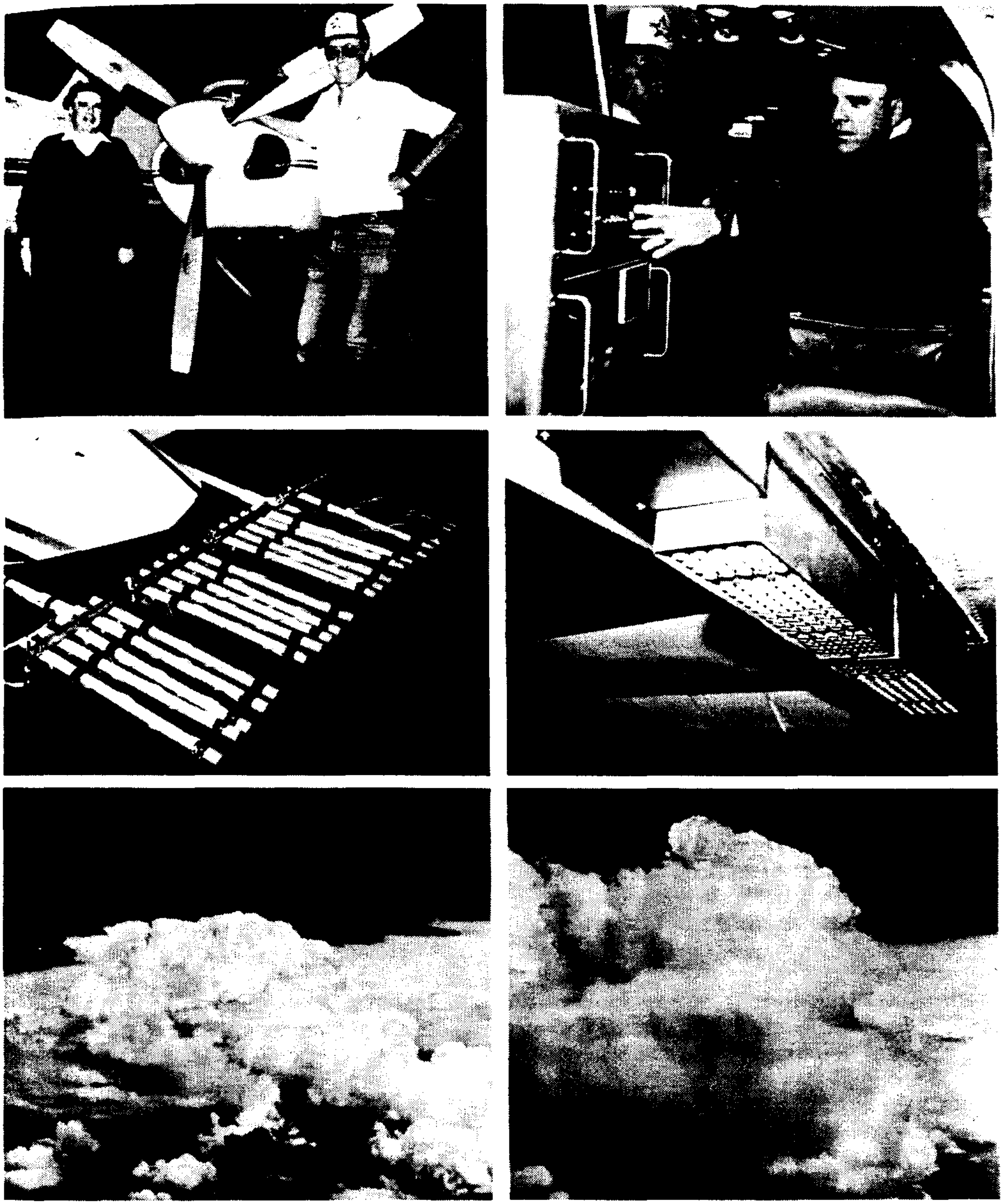
<u>Upper:</u> Office entry at Mathis Field, San Angelo, TX. <u>Center:</u> Office and antenna for Satellite Weather Data Acquisition. <u>Lower:</u> Computer system for weather data acquisition and the display board for weather charts and relevant data.







Upper: AI radar trailer and the antenna components for the C-band weather radar system, the main interrogator/transponder antenna for aircraft identification and tracking, and the VHF and UHF antennas for general communications. Center: The radar console, the "nerve center" during cloud seeding operations, and the radar trailer interior showing space for any visitors. Lower: View of the AI mobile weather radar facility at Mathis Field, San Angelo, Texas.



Upper: Bill Woodley (Project Supervisor) and Norris Veverka (cloud seeding pilot). Center: Burn-in-place and ejectable cloud seeding devices shown on their special mounting racks. Lower: Cloud on left showing supercooled liquid water, is a possible candidate for seeding. Cloud on right has been seeded and shows the conversion of supercooled liquid cloud droplets to ice crystals (glaciation).

1.0 INTRODUCTION

1.1 The Need for Water in Texas

Texas is a large state with a growing population and diverse economy. The State has a total land area of 267,339 square miles. The 1980 census listed a population of about 14.2 million people. The State's population is projected to grow to 17.8 million by 1990 and 20.9 million by the year 2000. It is a state that has long recognized the value of fresh water, as evidenced by its extensive water management programs which include irrigation projects and conservation efforts.

Texas has a huge appetite for water. Approximately 19.2 million acre-feet of Texas water (one acre-foot is 325,851 gallons) are used each year to meet the needs of households, industry, irrigation, steam-electric power generation, mining and livestock. Nearly 70 percent (13.4 million acre-feet) of the total water available each year is consumed by farmers and ranchers for irrigation to produce food and fiber to meet the demands of both the State and the Nation. By the year 2000, it is projected that 22.3 million acre-feet will be needed to meet the demands of the State, assuming that agricultural water use is held at 13.4 million acre feet. Virtually all of this water is ultimately produced by precipitation and by pumping from ground storage. A map of the Texas average annual precipitation for the years 1950 through 1980 is provided in Figure 1. It is important to note that average annual precipitation increases from near 8 inches in the west to over 56 inches in the east.

Although the overall supply of fresh water is usually sufficient to meet current needs in Texas, its distribution does not correspond to the areas of greatest need. If additional water sources are not found in some regions of the State, serious water shortages will adversely affect the local economies. This is especially true in the fertile but semiarid Texas High Plains area where the Ogallala aquifer, the major source of municipal and irrigation water, is being exhausted. Currently, the Ogallala supplies irrigation water for 5.9 million acres. However, at present annual use trends it is estimated that by the year 2000 the Ogallala will only supply water to about 2.2 million acres. Not only is water becoming more scarce, it is also becoming more expensive to obtain as the water table declines and pumping costs continue to rise.

When droughts are factored into the Texas water equation, the potential for serious water problems is increased. The recent history of Texas drought has been addressed by Riggio et al., (1987), and it brings the importance of adequate precipitation into sharp focus. At least one serious drought has plagued parts of Texas in every decade of the 20th century. The most catastrophic Texas drought was the state-wide dry spell that began in 1949 and ended in 1957. Wells ran dry, rivers stopped flowing and ranchers and farmers struggled to survive.

Since then, droughts of shorter duration and severity have plagued various areas of the state. In the Edwards Plateau portion of the state which includes Tom Green County and the City of San Angelo, other drought periods have included the years 1933-1934, 1947-1948, 1962-1964, and 1982-1984. It was very dry over the southern portion of the Edwards Plateau in 1989, including the area just south of San Angelo. However, it is not

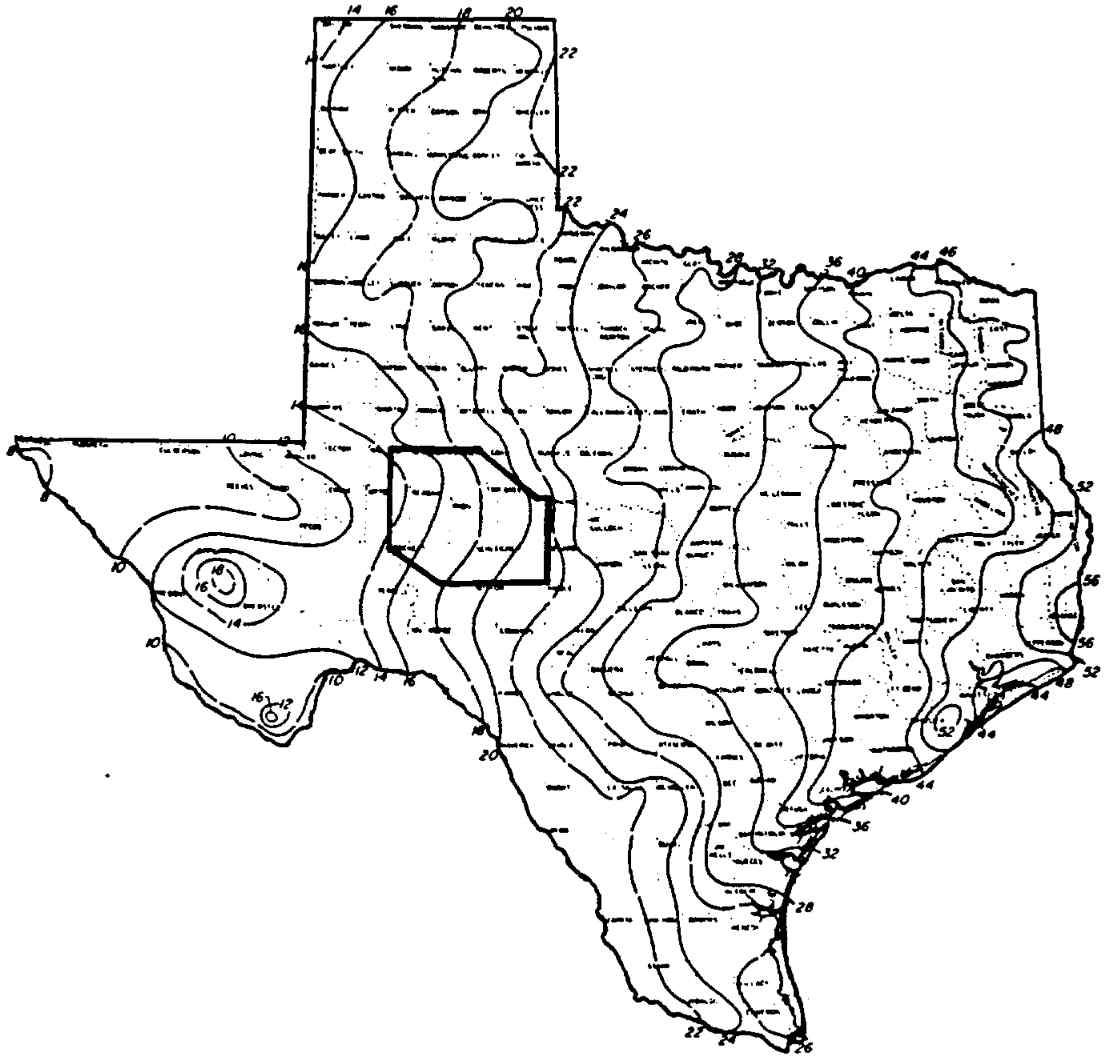


FIGURE 1. Texas mean annual precipitation in inches, 1951-1980. San Angelo Rain Enhancement Program target area is highlighted in bold outline.

clear whether this is a temporary weather aberration or the beginning of another extended drought period.

In order to meet the water needs of Texas, and specifically in the Texas High Plains, additional and cost effective fresh-water supplies must be developed. One relatively new technique of providing additional fresh water is to tap the available atmospheric moisture which does not naturally fall as rain. The value of this supplemental water source has been calculated by exploratory studies of the Texas Department of Water Resources (Allaway et al., 1975; Lippke, 1976; and Kengla et al., 1979). These studies indicate that cloud seeding over an 8.1 million acre project area of the southern High Plains, yielding 10 percent additional rainfall during the growing season, would produce an overall expansion in regional output of approximately $3.68 million plus an additional $2.30 million to the regional income.

Studies such as these, showing the value of increased water, explain why Texas has a history of both meteorological research and cloud seeding efforts to enhance natural precipitation. For example, the Colorado River Municipal District (CRMWD) in Big Spring, Texas sponsored a cloud seeding program which ran continuously from 1971 through 1988 (18 years). The twofold purpose of this program was to increase precipitation runoff for storage in the CRMWD reservoirs and to increase rainfall for use by agriculture. Jones (1985 and 1988) made use of historical rainfall records (1936-1970) to calculate percent of normal rainfall at target and control stations. Target-control statistical regressions were developed and these were used to predict rainfall during the operational period (1971-1988). The predicted and observed target rainfalls were then compared. Both analyses suggest that cloud seeding increased rainfall between 10% and 30% in the target area.

A second analysis by Jones (1988) which summarizes the yields of unirrigated cotton in and around the target since seeding began in 1971, indicates increases of cotton production of 48% and 45% within and somewhat downwind of the target. The increase in cotton production over the same time period in the counties upwind of the seeded area was only 8%. If one assumes that rainfall has been one of the major controls of cotton production over the entire region, this result might be interpreted as further evidence for seeding-induced rain increases.

1.2 The San Angelo Rain Enhancement Program

During the latter stages of the 1982-1984 drought over the Edwards Plateau, the City Council and the Manager of the City of San Angelo investigated the potential of cloud seeding for mitigating the drought over the city's watershed. Aware of the long-term CRMWD program and of continuing progress in cloud seeding research, on November 8, 1984 the Council issued a solicitation for a qualified weather modification contractor. North American Weather Consultants (NAWC) answered this solicitation and was selected to conduct the operational cloud seeding program.

The program was based on dynamic seeding concepts (e.g. Woodley, et al., 1982; Gagin, et al., 1986; Rosenfeld and Woodley, 1989) and had as its goals the replenishment of surface reservoirs, ground water supplies and increased precipitation over the residential areas to reduce demand for municipal water. It was recognized that increased rainfall would also benefit the farming and ranching communities.

NAWC conducted the program each summer through 1988 and submitted reports on their operations and apparent results (Girdzus and Griffith, 1986; Griffith and Girdzus, 1987; Risch and Griffith, 1988; and Girdzus and Griffith, 1989). The last report indicated overall target increases of about 12%, using linear regression procedures and historical rainfall records.

During the fall of 1988, the City of San Angelo issued another request for proposals for continuation of their cloud seeding program. Atmospherics Incorporated (AI) answered this RFP and was selected to conduct the City's 1989 cloud seeding program. This document is the Final Report for the first year of seeding operations under AI supervision.

2.0 APPROACH TO SEEDING

During the 1989 season, AI employed scientifically sound and socially acceptable weather modification procedures in an attempt to stimulate more rainfall over the San Angelo watershed. The primary approach was focused on "dynamic seeding", a technology where ice nucleating material is dispensed near cloud tops to enhance growth mechanisms of individual cloud turrets. In some instances, particularly at night, the seeding was accomplished at cloud base. This technology is focused on the microphysical properties of clouds to enhance the efficiency of precipitation mechanisms. The physical basis for cloud seeding to enhance rainfall by these two seeding approaches is addressed in the following paragraphs. A more comprehensive discussion can be found in Appendix 11.1.

When conducting dynamic seeding the individual cloud towers growing within the convective cells which that make up most summer cloud systems in Texas, were seeded near their tops. Typical cloud top heights were 5.5 to 6.5 km (18,000 - 21,000 ft.) and top temperatures were -8°C to -12°C (18°F to 12°F). The seeding devices were ejectable flares each producing 20 gm of effective silver iodide (AgI) smoke particles during their 1 km free-fall through the upper portion of the cloud. An average of 2 to 3 flares were ejected per cloud tower whenever the criteria were met for strong updrafts <u>and</u> supercooled liquid water.

Dynamic seeding in the 1989 operational setting was accomplished within the context of the conceptual model that guided the Florida Area Cumulus Experiment (FACE) (Woodley et. al., 1982). Ideally, according to the <u>initial</u> steps in this conceptual model, the seeding should produce more rain from individual cells and groups of cells through the following steps:

- Intensive AgI-seeding of the updraft portion of a vigorous supercooled cloud tower rapidly converts the supercooled water to ice.
- The released latent heat due to freezing and deposition increases the buoyancy of the cloud tower, increases the updraft and makes it grow taller.
- The larger convective cell, of which each cloud tower is a part, produces more rainfall by virtue of its greater height and larger area.
- The enhancement of the rainfall from the treated convective element leads to enhanced water loading which, in conjunction with the increased entrainment of drier environmental air into the cloud, invigorates the downdrafts. The downdrafts then interact with the subcloud ambient winds to increase convergence and trigger adjacent cloud growth. Some of these new clouds will in turn produce precipitation, resulting in further expansion of the cloud system.

This conceptual model of cloud growth following treatment is supported by the observations that taller convective cells precipitate more. Observations of natural convective rain clouds in Florida (Gagin et. al., 1985) indicate that an increase of cell top height by 20% nearly doubles its rain production. If a seeding-induced enlarged cloud behaves as a natural cloud which reaches the same top height, the rainfall of the treated cloud will be increased accordingly.

Despite its obvious value in augmenting rainfall, dynamic seeding is not the only appropriate seeding approach in West Texas. When additional cloud-growth potential is low and the natural clouds are expected to be very tall, dynamic seeding may not produce a more efficient or effective natural precipitation process. This is most likely when the cloud bases are relatively high and cold (i.e. < +10°C). In these situations, cloud-base seeding may be more effective.

The conceptual model for this "microphysical" seeding approach assumes a concentration of natural ice nuclei less than required for optimum precipitation processes. Adding artificial ice nuclei will increase the ratio of ice crystals to supercooled liquid water, thus increasing the overall efficiency of the cloud system to produce precipitation. It is important to emphasize that this approach attempts to stimulate ice crystal formation at the warmest possible temperature where natural ice nuclei are scarce.

Therefore, it must be emphasized that the choice of an individual seeding approach is not a matter of mere whim. Which system is applied depends on the meteorological conditions. When the cloud bases are high and cold, the cloud's precipitation-forming mechanisms can be quite inefficient. The addition of a few ice nuclei per liter can result in the formation of ice crystals which will grow to precipitation size, eventually falling and melting to produce additional precipitation.

3.0 COMPONENTS OF THE SAN ANGELO RAIN ENHANCEMENT PROGRAM

3.1 General

The 1989 San Angelo operational cloud seeding program under the field supervision of AI, was designed to use state-of-the-art satellite weather data acquisition systems, high performance aircraft, pyrotechnic cloud seeding devices, weather radar, and some basic airborne instrumentation. These components allowed the field operations staff to recognize and act upon seeding opportunities for rain enhancement over the target area shown in Figure 2. The primary objective of the program was to produce supplemental rainfall over the watersheds that feed San Angelo's two main reservoirs, Twin Buttes southwest and O.C. Fisher northwest of the city. Airborne seeding was mainly concentrated on suitable clouds within 30 nm of these reservoirs to increase and runoff from tributary streams and precipitation over the reservoirs themselves. Seeding at greater distances was conducted in a few instances when the cloud systems were expected to move toward the storage reservoirs. In meeting the primary objective, recharge of the area's shallow aquifers was also a strong consideration. One of the secondary objectives of the program was to increase rainfall over the metropolitan areas in order to decrease the demand for municipal water.

Many of the seeding flights were conducted at or near cloud top using ejectable pyrotechnic seeding devices. Some of the airborne operations, particularly those at night, were conducted at cloud base using end-burning pyrotechnic seeding devices affixed to special mounting racks on each wing. Cloud base seeding was the preferred mode when large highly organized cloud systems traversed the target area. The number of seeding devices used was a function of the strength and areal extent of each storm system.

3.2 Facilities and equipment

3.2.1 Field office

AI leased office space from Ranger Aviation at Mathis Field to serve as project headquarters. The small building was used to house the computer components of the satellite weather data acquisition system and to provide office space for project personnel. The radar meteorologist (operations supervisor) utilized a portion of the space for data compilations, report preparation, preliminary analysis studies, and general administrative requirements. The cloud seeding pilot used some of the space for final flight form preparation, aircraft operations summaries and computerized cloud seeding data files. Additional rooms in the building were used for supplies, spares, and general storage.

3.2.2 Weather data acquisition system

AI installed a down-link satellite weather data acquisition system at the field office in order to obtain a broad range of specific weather data. This versatile system provided the following products:

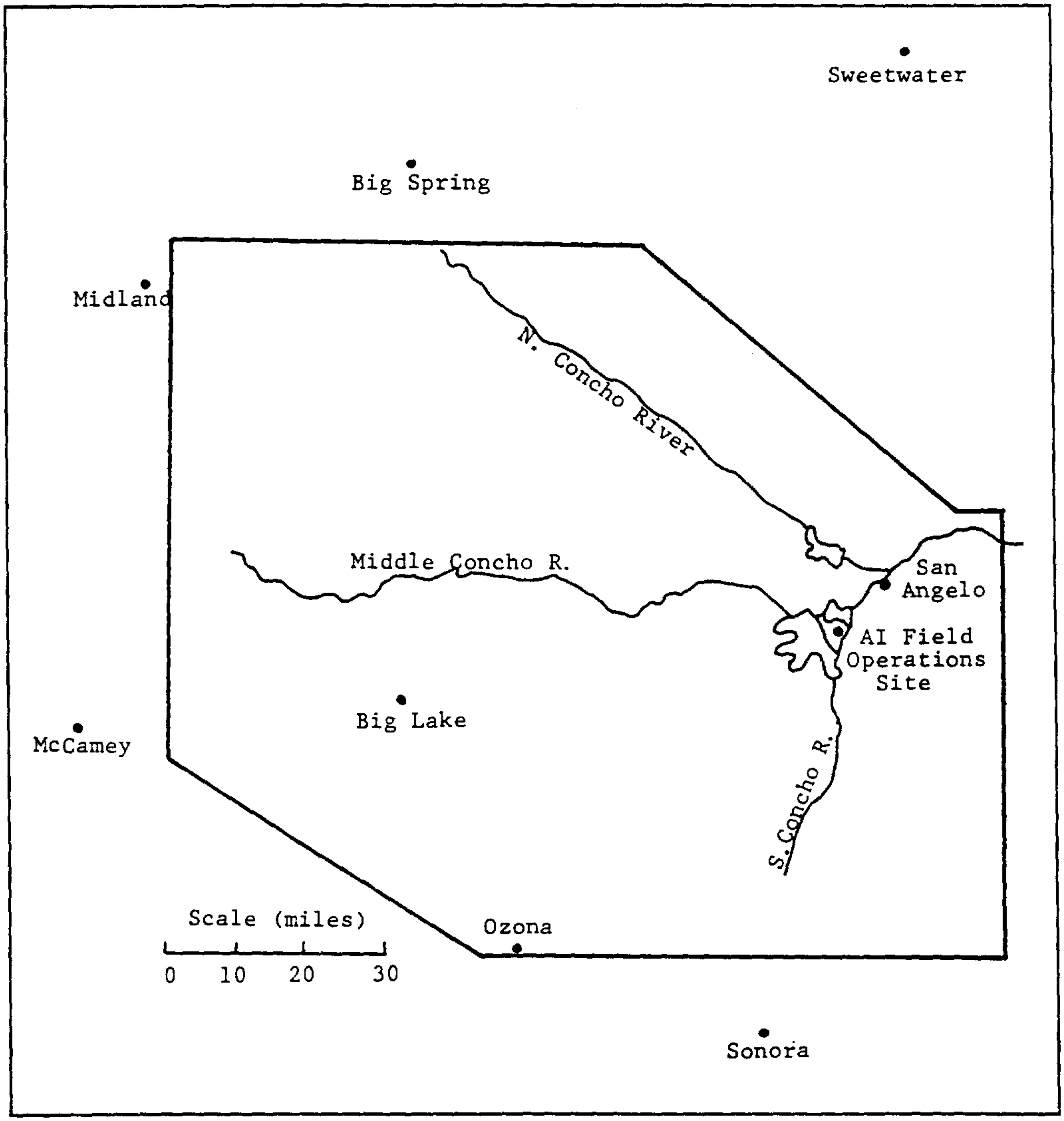


FIGURE 2. Target area for the San Angelo Rain Enhancement Program.

- hourly weather reports
- upper air soundings
- analyses at various atmospheric levels
- weather forecasts
- weather watches and warnings
- satellite pictures

A PC/AT computer was used to scan the incoming data and to print out the weather information selected in advance as necessary to the conduct of the program. GOES photographs were printed on an Alden 9315/TRT Compact Facsimile Recorder and weather maps were reproduced on an Okidata Microline 293 printer.

3.2.3 Radar

The AI operational radar was a C-band Enterprise Electronics system with L-band aircraft transponder display capability used for coordination of all seeding flights. The trailer-mounted radar was sited just beyond the northeast corner of the field office, about 100 yards SW of the National Weather Service office. Although this was a convenient location for the radar, it had two disadvantages. First, the lower portions of precipitation echoes occurring north-northwest through southeast were partially blocked by nearby hangar obstructions. This was somewhat of a problem whenever precipitation echoes were moving into the target from these directions. Second, the energy radiated by the radar interfered with the satellite transmissions of weather data from the satellite to the receiving antenna located at the northwest corner of the field office. In this latter instance weather data acquisition was normally active only during select periods and, in most cases, the radar was either not active or could be temporarily shut down during these required transmission periods.

The radar meteorologist was charged with coordinating all seeding operations, assessing echo top heights, and logging reflectivity values and precipitation echo patterns. Because of the need to focus on multiple precipitation areas and rapidly changing storm characteristics, operation of the radar system remained in the total manual mode. During the course of seeding operations, PPI scope overlays were prepared at 15-30 minute intervals, showing echo sizes and positions, echo top heights, reflectivity values, and storm motions. As the seeder aircraft climbed to altitude, the radar meteorologist closely observed the field of echoes to determine cell vigor, organization and lifetime. Appropriate information was radioed to the pilot as an assist with the selection of suitable seeding targets. During operations the radar meteorologist monitored the weather data system for NWS severe storm warnings specific to the active and anticipated seeding areas. Additionally, the radar meteorologist also assessed any severe echo development via direct radar measurements.

Basic characteristics of the radar system are provided in Appendix 11.5.

3.2.4 Aircraft

The AI aircraft furnished to this program was a Cessna 421C Golden Eagle III. The aircraft is turbocharged, pressurized and certified for IFR flight in known icing conditions. Deicing systems are installed on the propellers, leading edge wing surfaces and leading edge tail surfaces. The 421C is powered by 375 hp engines, has an absolute ceiling of 30,200 ft. with a flight endurance in excess of five hours. Performance and specifications are listed in Appendix 11.6.

The primary function of the aircraft was to accomplish seeding of suitable convective clouds using fixed or ejectable pyrotechnic seeding devices each containing 20 grams of effective silver iodide. As an aid to the seeding missions, the aircraft instrumentation also included an airborne radar system used primarily to ensure the safety of the aircraft and crew during cloud penetrations and general movement around the storm systems.

Additionally, the cloud seeding aircraft also carried an airborne data acquisition system. This is a computer-controlled package specifically designed to monitor the aircraft's navigational and meteorological instrumentation. Machine language software supervises the acquisition of raw data on an interrupt-driven basis. The computer provides alpha numeric data on a 24-line, 40-character wide display, and graphical data in a 240 x 170 point display. The real time display routines are written in BASIC + to facilitate simplified program modifications. All data are acquired through a general purpose system called Computer Automated Measurement and Control (CAMAC), an international standard defining the hardware configuration for interchangeable data acquisition modules. Data are recorded on 5.25 inch floppy disks. The system is easily used in single-pilot operation as no keyboard entries are required to start and run the system. The recorded data consists of the following:

- time (crystal clock)
- VOR (bearing from station)
- DME (distance to/from station)
- TAS (true airspeed)
- pressure altitude
- aircraft heading (compass)
- aircraft vertical velocity (Ball Variometer)
- aircraft azimuth from radar (calculated)
- aircraft range from radar (calculated)
- aircraft position -- latitude (LORAN)
- aircraft position -- longitude (LORAN)

- temperature (Rosemount)
- relative humidity (Rotronics)
- liquid water content (Johnson-Williams)
- icing rate (Rosemount ice detector)

The aircraft also carried a forward looking CCD video camera for documentation of cloud developments and aircraft maneuvers around the clouds. All voice transmissions to, from and within the aircraft were recorded on the video tape. The video system was mated to the data acquisition package such that a real-time display of the meteorological and aircraft readouts in engineering units could be switched to the video monitor for instant readout by crew members.

Reduction of data obtained during select missions was accomplished immediately following each flight via one of the computer systems located at the project field office.

3.2.5 Nucleating systems and devices

Two separate nucleating systems were installed on the 421C. These included:

- one 200-position fuselage-mounted rack for mounting and ejecting pyrotechnic seeding devices during cloud-top seeding or when penetrating growing cumulus
- two 20-position wing racks for mounting and igniting end-burning pyrotechnic seeding devices used during sub-cloud or in-cloud missions

Three types of pyrotechnic seeding devices were available for use on the San Angelo project. These were:

- 10-gram ejectable units which can be dropped into individual convective cells, falling 3,000 ft. in 30 seconds before burn-out
- 20-gram ejectable units which can also be dropped into the top of each convective tower, or at some temperature level such as -10°C (14°F). This unit falls 6,000 ft. in 60 seconds before burn-out.
- 20-gram end-burning units which produced silver iodide particulates at a rate of 3.3 grams per minute

3.2.6 Communications

A proper communications network is absolutely essential to any professional level weather modification field program, either research or operations. Frequent contact between all operational personnel is mandatory.

As the primary operational frequency on this program, AI furnished FM communications operating on 464.5/464.9 MHz. A base station was installed in the radar trailer and mobile units were a part of the cloud seeding aircraft and project vehicles.

As a back-up to this primary communications system, AI provided additional FM radio equipment operating on 151.625 MHz. This equipment was also available for use in the aircraft and project vehicles.

3.2.7 Raingage network

A recording raingage network was operated by the City of San Angelo during the 1989 program. The network consisted of 13 Belfort weighing-bucket raingages recording on paper strip charts and 12 automatic data transmission hydrometeorological stations. Their locations are noted in Figure 3.

This network was purposely located in the drainage area for San Angelo's two major reservoirs. An employee of the City of San Angelo (Richard Jackson) maintained the network. Additional gage information was obtained from long-term gage sites that included Garden City, Sterling City, Cope Ranch, Funk Ranch, Water Valley, Water Valley 10NNE, San Angelo, Mertzon, Mertzon 10NE, Eldorado and Ozona. It should be noted that the Mertzon site ceased operation in 1987, whereas the Mertzon 10NE site began its operation in 1977. These two stations figure prominently in the assessment of seeding effects presented in Section 5.0.

Each recording raingage was checked once weekly. On each recorder chart the operator noted date, gage identifier, time installed and removed, and particulars related to any failures. The catch bucket used for the weighing gages was charged with water so that the gage initially registered approximately two inches of rainfall on the chart. The gage pen was inked and the clock wound. The initial charge of the bucket stabilized the weighing mechanism of the gage, providing higher quality recordings than if the bucket was dry at the time rainfall occurred.

The twelve automatic data transmission hydrometeorological stations measured precipitation and stream stage. Each data collection platform contained a microprocessor and radio transmitter to collect, store and relay data at preset or event-activated intervals. The messages were relayed via satellite to any receiving site monitoring channel 36 of the GOES WEST satellite. The San Angelo raingage network was in operation for the total duration of the program.

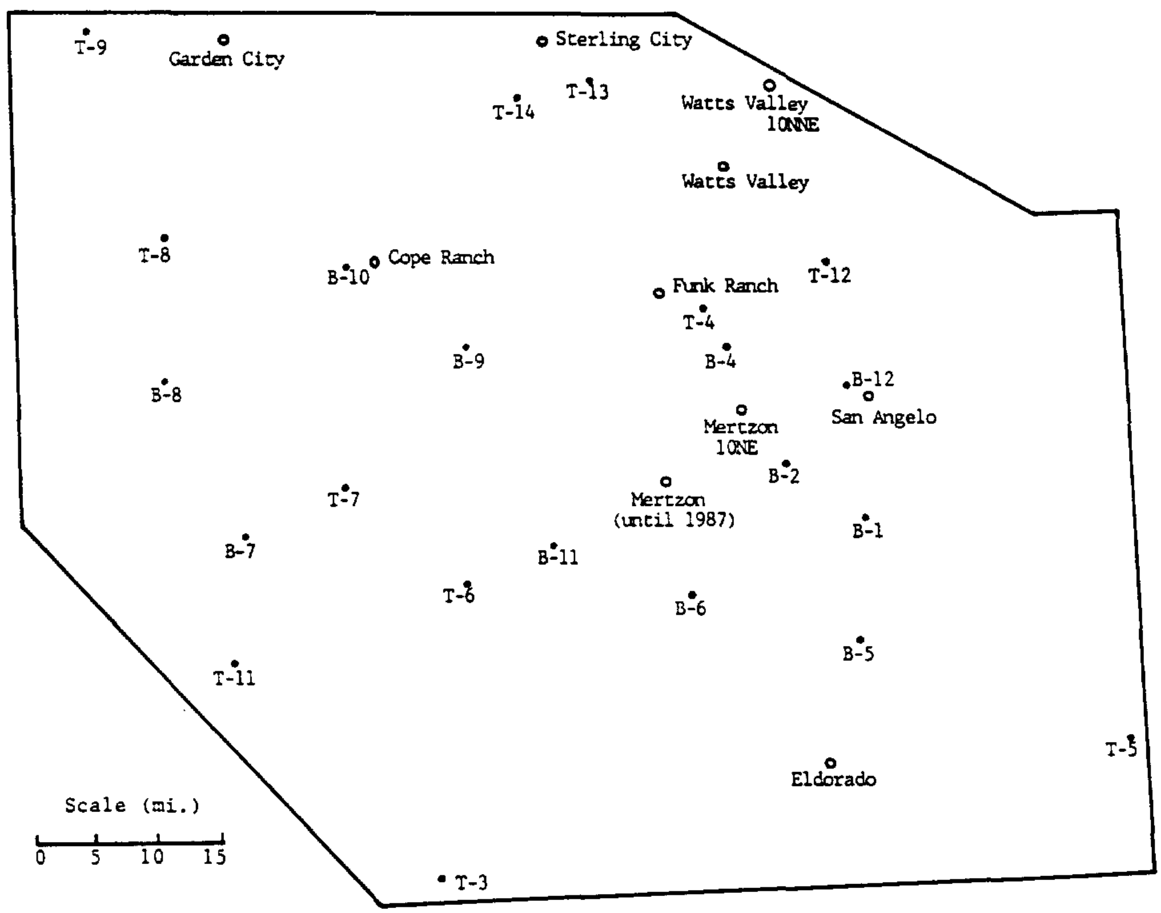


FIGURE 3. San Angelo raingage network (with supplemental long-term gages). Long-term stations are indicated by an "O", analog recording weighing gages are indicated by the letter "T", and digital recording tipping bucket gages are indicated by the letter "B".

4.0 OPERATIONS

4.1 Weather during the program

The San Angelo Rain Enhancement Program focuses on precipitation. Therefore, it is fitting to use rainfall as the important parameter to characterize the weather during the operational period. An isohyetal map of the May through September rainfall over the San Angelo target is provided in Figure 4. The plotted data came from the San Angelo network, less the few gages that were not operative throughout the entire period.

In constructing Figure 4, gages B-10 and B-11 were not available for the entire period, nor were gages T-13 and T-14. In the case of gages T-13 and T-14, their records were combined to provide an average total. The total (6.69 in.) was plotted at the mid-point of the two gages. The record was not used for gage B-12, which was located on the top of the dam for Twin Buttes Reservoir. Very little rain was reported at this gage, even though it was less than 1 mile from the National Weather Service gage at Mathis Field where 9.84 in. was recorded in the 5-month period. Apparently, the airflow over the dam site was such that the collection efficiency of the gage was seriously degraded.

The plot and analysis of the 5-month raingage values show wetter conditions beginning to the southwest of San Angelo and extending northeastward and eastward, then broadening into the extreme eastern portion of the target. The gradients in rainfall are especially great southwest of San Angelo, where the transition to dry conditions was abrupt. It was quite dry during the period in the south and south-southwest portions of the San Angelo watershed, and this region of drought extended past Sonora toward Del Rio and eastward into the Hill Country.

Figure 4 illustrates why there was no runoff from the south into Twin Buttes reservoir. There was not enough rain in this region along the South Concho to produce surface runoff. Only along the Middle Concho and North Concho did the surface flow react to the various rainfall occurrences.

It is interesting to determine how individual rain events contributed to the rainfall distribution shown in Figure 4. A step in this direction is the bar-graph plot of the mean rainfall within the San Angelo watershed during the 1989 season. This information is presented in Figure 5. The asterisks (*) on the calendar plots indicate cloud seeding flights. Note that in some cases the mean rainfall was calculated over more than one day. Twenty-five gages normally contributed to the average. The long-term gages were not available for this plot.

Although rain was reported somewhere in the San Angelo network on 60 of the 183 operational days, a study of the plot reveals that the few heavy rain cases contributed most of the total rainfall. The frequency of rain was greatest in May, early June, mid to late July and early August. The frequency was virtually zero in the latter halves of June and August and during most of September and early October.

The isohyetal plot in Figure 4 shows that most of the rainfall events affected the region to the immediate west of San Angelo and the area to its north, northeast and east.

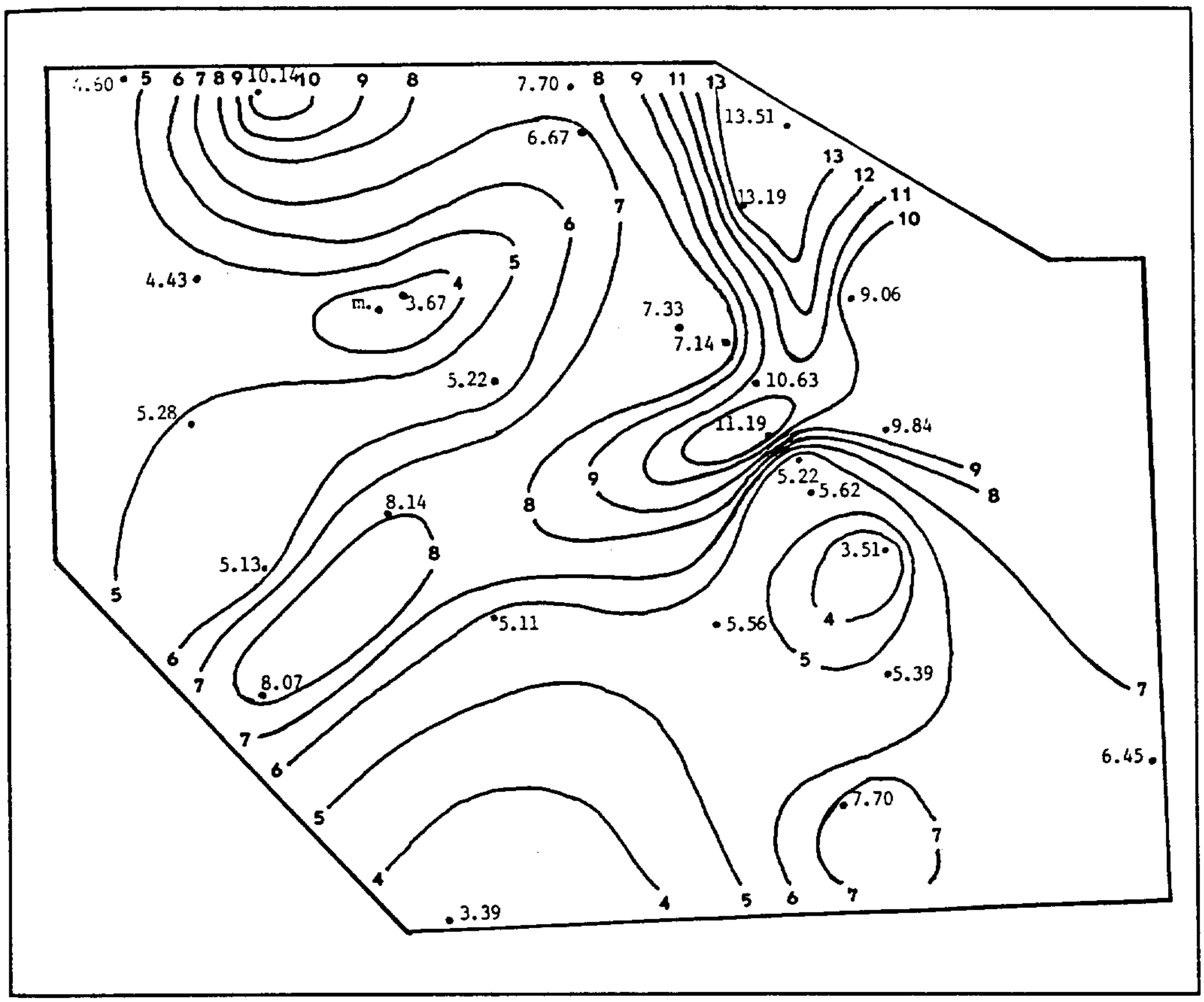


FIGURE 4. Total rainfall in inches for the period May-September 1989. Stations B10, B11, and B12 are considered unreliable. Stations T13 and T14 were combined to provide one record.

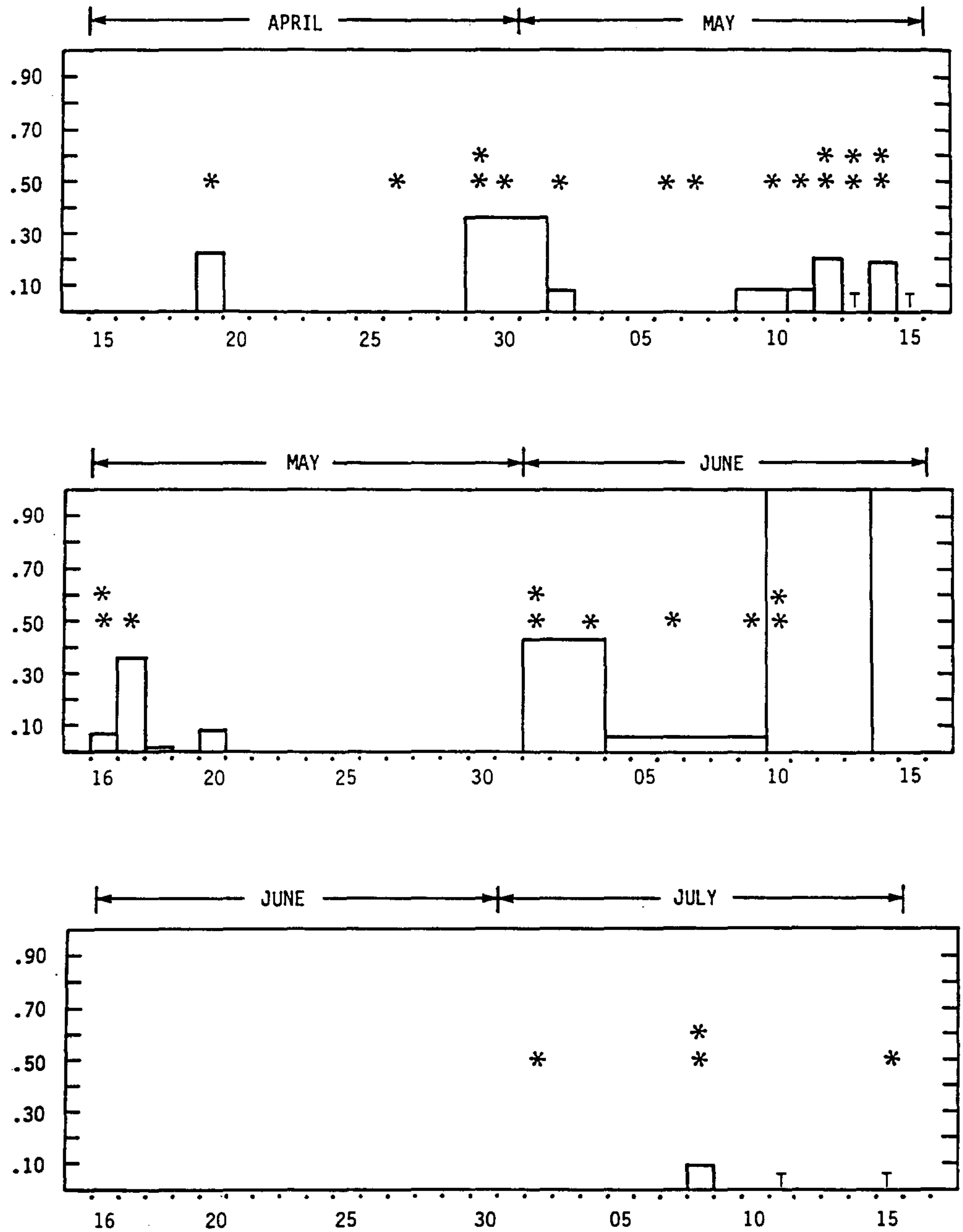


FIGURE 5. Bar graph plot of the mean rainfall within the San Angelo watershed during the May-September 1989 season. The asterisks indicate the occurrence of a cloud seeding flight on that day.

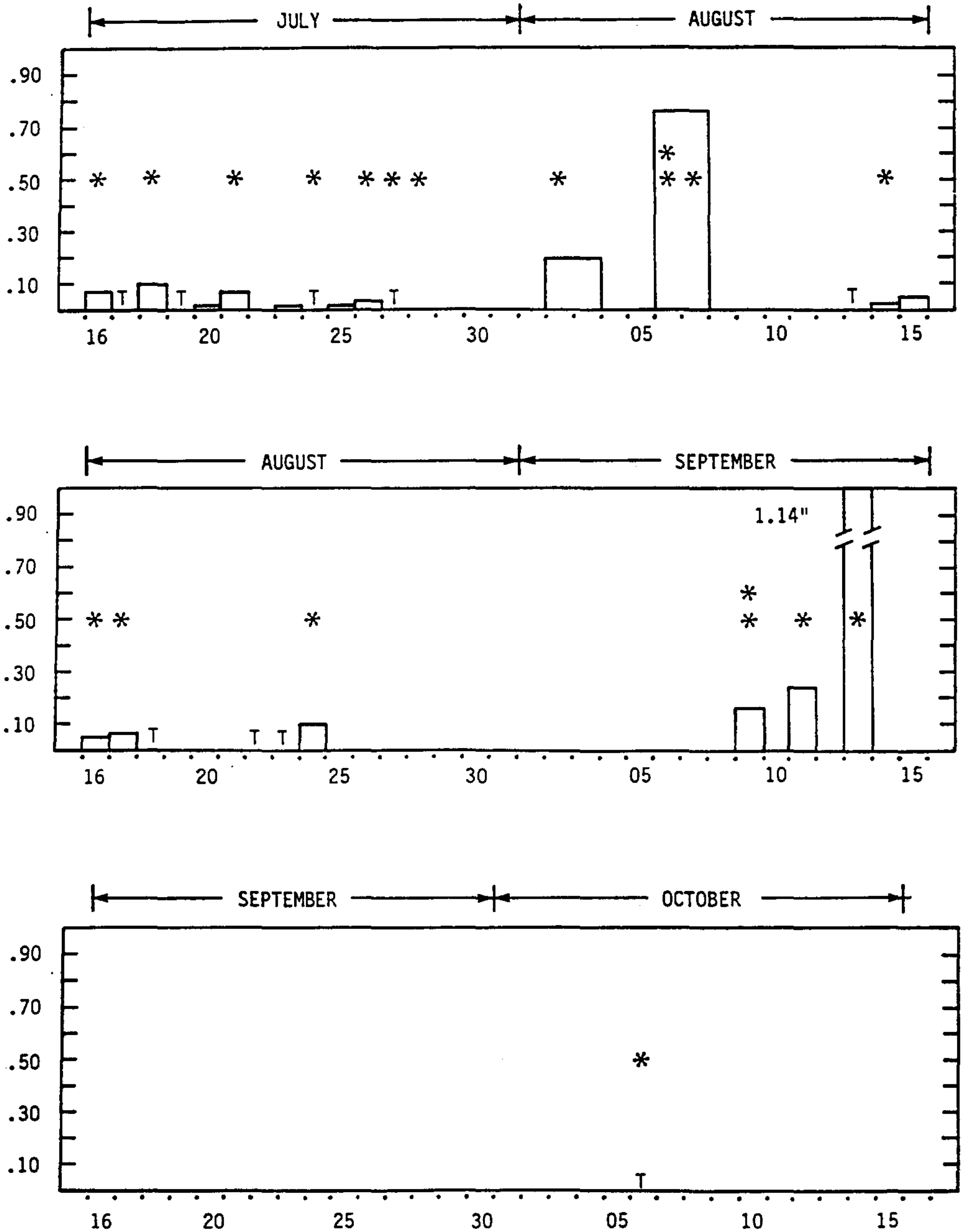


FIGURE 5. (Continued)

The thunderstorms associated with these big events either formed west of San Angelo and moved northeast or they moved southeast into San Angelo, dissipating only a short distance to the south of the city. All of these systems were seeded.

A more-detailed discussion of the weather during the project period is provided in Appendix 11.2.

4.2 Seeding Operations

AI personnel were quite active during portions of the 6-month program. The relevant day-to-day flight operational information is presented in Table 1.

The flight duration in column 5 of Table 1 is the elapsed time between engine start and engine stop. The cloud base temperature in column 6 is included because the effects of seeding may be influenced by the temperature at cloud base. The column headed "Seeded Towers" refers to the number of single cumulus entities that were penetrated at altitude and seeded with ejectable pyrotechnic seeding devices. This parameter is not defined when seeding was conducted at cloud base. The columns showing number and type of seeding devices are self-explanatory, as are the other columns of Table 1.

A summary of the operational seeding flights during the six months of the San Angelo Rain Enhancement Program is provided in the following Table 2.

A plot of each seeding event for the 1989 program is provided in Figure 6, where a seeding event is defined as the activation of at least one ejectable or end-burning flare. The positions of the SWCP randomized AgI seedings (research) on 14 and 17 August are included in this plot, because AgI flares were used during the flights. This plot will play a role in the evaluation of the seeding activity, and all AgI seeding positions must be included.

Examination of Figure 6 reveals that most of the 613 seeding events took place to the immediate southwest, west and northwest of San Angelo, which is marked by its call letters SJT. Very little seeding took place to the immediate south and more distant southwest and west portions of the target and operational areas. This is due to a general lack of suitable clouds and to the general focus on the areas immediately upwind of San Angelo.

Of the 49 operational seeding flights in 1989, 29 were cloud-top flights using ejectable flares and 14 were cloud-base flights using end-burning flares. On the 6 remaining flights both on-top and base seeding was conducted during each event. All of the seeding at night was conducted at cloud base.

TABLE 1

SAN ANGELO PROJECT
SEEDING FLIGHT INFORMATION

FLT. NO.	DATE	FLT. START (CDT)	FLT. STOP (CDT)	FLT. DUR (HRS)	CLD. BASE T (°C)	SEEDED TOWERS	TOTAL FLARES	TYPE OF FLARE (EJ or EB)	TIME OF FIRST SEEDING	TIME OF LAST SEEDING	TOTAL SEEDING HOURS	COMMENTS
1	4/16	1030	1150	1.3	--	--	--	--	----	----	---	FAA Checkout
2	4/16	1500	1618	1.3	--	--	--	--	----	----	---	FAA Checkout
3	4/19	0540	0720	1.7	7	8	14	EJ	0626	0635	0.2	Visibility limited at night
4	4/20	0830	0948	1.3	--	--	--	--	----	----	---	Cloud reconnaissance
5	4/20	1242	1350	1.2	--	--	--	--	----	----	---	Cloud reconnaissance
6	4/26	1810	2055	2.7	9	27	60	EJ	1844	2008	1.4	Dry line moved through area
7	4/29	1325	1545	2.3	7	12	35	EJ	1358	1435	0.6	High Cld bases, little rain
8	4/29	1633	1823	1.8	7	17	37	EJ	1719	1758	0.7	Clds seeded near San Angelo
9	4/30	1814	2039	2.4	10	58	140	EJ	1835	2005	1.5	Conv. line from San Angelo to the SW
10	5/2	1705	1940	2.6	10	26	60	EJ	1719	1919	2.0	Clouds moved down N. Concho
11	5/6	2125	0005	2.7	9	4/NA	17/6	EJ/EB	2155	2256	1.0	Storm tracked SSE toward San Angelo
12	5/7	1622	2012	3.8	14	46/NA	77/8	EJ/EB	1653	1942	2.2	Very tall storms with some hail
13	5/10	0205	0535	3.5	12	NA	33	EB	0220	0520	3.0	Good clouds near San Angelo
14	5/11	1852	2235	3.7	14	NA	27	EB	2025	2304	2.3	Embedded convection
15	5/12	0740	0910	1.5	14	7	41	EJ	0810	0843	0.6	Embedded convection, rain in San Angelo
16	5/12	1705	1930	2.4	19	36	78	EJ	1742	1907	1.4	Worked strong storm W of San Angelo
17	5/13	1110	1310	2.0	19	17	43	EJ	1146	1256	1.1	Strong storm NW of San Angelo
18	5/13	1650	1750	1.0	20	10	18	EJ	1722	1732	0.2	Good clds but exited target to the east
19	5/14	1212	1524	3.2	20	50	80	EJ	1335	1458	1.4	Seeded clouds along N Concho
20	5/14	1645	1830	1.7	20	30	59	EJ	1735	1758	0.3	Seeded clouds near San Angelo, heavy rain
21	5/15	1745	1818	0.5	21	0	0	--	---	---		Cloud reconnaissance
22	5/16	1144	1327	1.7	22	20	37	EJ	1227	1303	0.6	Seeded clouds NNW and N of San Angelo
23	5/16	1636	2004	3.5	22	38	103	EJ	1712	1935	2.4	Huge S clds in line to NW
24	5/16	2240	0102	2.4	22	NA	29	EB	2312	0051	1.7	Good inflow seeding S of San Angelo
25	6/1	0145	0333	1.8	17	NA	22	EB	0203	0325	1.4	Seeded conv. line to south of San Angelo
26	6/1	2109	2347	2.6	17	NA	38	EB	2130	2335	2.1	Seeded cloud moved down N. Concho
27	6/2	2009	2112	1.1	18	NA	0	--	---	---	---	Cloud reconnaissance
28	6/3	1414	1510	0.9	4	NA	0	--	---	---	---	Cloud reconnaissance
29	6/3	2010	2240	2.5	22	NA	39/18	EJ/EB	2039	2205	1.4	Treated line of clouds approaching SJT
30	6/6	1728	1931	2.1	15	10	26	EJ	1815	1853	0.6	Seeded to distant southwest
31	6/9	1112	1319	2.1	16	35	77	EJ	1151	1257	1.1	Seeded towers close to SJT to S,SW & W
32	6/10	1308	1502	1.9	21	109	199	EJ	1329	1436	1.1	Seeded short line to south of SJT
33	6/10	1550	1903	3.3	21	NA	37	EB	1705	1902	1.9	Seeded strong line, moved into San Angelo
34	6/13	0625	0739	1.2	19	NA	0	--	--	--	--	Cloud reconnaissance
35	6/13	1407	1612	2.1	10	NA	0	--	--	--	--	Cloud reconnaissance

TABLE 1 (Cont.)

SAN ANGELO PROJECT
SEEDING FLIGHT INFORMATION

FLT. NO.	DATE	FLT. START (CDT)	FLT. STOP (CDT)	FLT. DUR (HRS)	CLD. BASE T (°C)	SEEDED TOWERS	TOTAL FLARES	TYPE OF FLARE (EJ or EB)	TIME OF FIRST SEEDING	TIME OF LAST SEEDING	TOTAL SEEDING HOURS	COMMENTS
36	6/13	1824	1947	1.4	19	NA	0	--	--	--	--	Severe strm warning
37	6/21	0746	0906	1.3	--	0	0	--	--	--	--	Brown, Woodley & Wood to Austin
38	6/21	1030	1135	1.1	--	0	0	--	--	--	--	Brown, Woodley & Wood to San Angelo
39	7/2	2135	2325	1.8	13	NA	11	EB	2158	2308	1.7	High-based clds near SJT, hot day
40	7/8	1228	1433	2.1	15	44	73	EJ	1314	1503	1.8	Seeded clouds within 25 n.mi. of SJT
41	7/8	1624	1804	1.7	11	NA	7	EJ	1645	1718	0.6	Seeded clouds within 25 n.mi. of SJT
42	7/12	1000	1050	0.8	--	0	0	--	--	--	--	Cloud observation, no seed
43	7/14	1820	1940	1.3	11	0	0	--	--	--	--	Cloud observation, no seed
44	7/15	1706	1840	1.6	11	9	13	EJ	1742	1813	0.5	Brief seeding of clouds 30 n.mi. S of SA
45	7/16	1637	1906	2.5	10	NA	20	EB	1656	1837	1.7	Seeded clouds near SJT, high bases, hot
46	7/18	2005	2345	3.6	8	NA	22	EJ	2028	2310	1.7	Line of TRW's, excellent conditions
47	7/21	0605	0824	2.3	8	NA	12	EJ	0637	0740	1.1	Good conditions, widespread TRW's
48	7/24	1546	1733	1.6	11	4	4	EJ	1631	1656	0.4	Poor conditions, scattered airmass TRW'w
49	7/26	1920	2239	3.6	12	16	21	EJ	1958	2158	2.0	Very good conditions, RW+, tropical wave
50	7/27	1646	1904	2.3	12	6	11	EJ	1749	1840	0.9	Poor conditions, isolated airmass TRW's
51	7/28	1531	1744	2.3	17	6	7	EJ	1635	1720	0.8	Poor conditions, TRW cluster
52	8/2	1425	1746	3.4	13	15	47	EJ	1538	1724	1.8	Good seed conditions near San Angelo
53	8/6	1337	1631	2.9	14	10	32	EJ	1437	1610	1.5	Fair seeding conditions, scattered TRW's
54	8/6	1725	1946	2.4	14	2/NA	6/12	EJ/EB	1801	1910	1.2	Seeding in strong line, hvy rain at SJT
55	8/7	0515	0754	2.8	18	NA	8	EB	0546	0732	1.8	TRW+ over SJT and to SW, slow movement
56	8/9	1215	1250	0.6	NA	NA	NA	NA	--	--	--	Test Flt (equipment check)
57	8/16	1349	1710	1.5	11	1	4/9	EJ/EB	1443	1652	1.9	Poor seeding conditions near San Angelo
58	8/17	1739	1841	1.0	14	NA	7	EB	1758	1828	0.5	Base seeding near San Angelo, fair condts
59	8/24	2140	2255	1.3	17	NA	6	EB	2155	2243	0.8	Operational seeding to NW of San Angelo
60	9/9	1342	1644	3.0	14	13	51/5	EJ/EB	1443	1630	1.7	Operational seeding from SW-NW of SJT
61	9/9	1716	1830	1.2	14	NA	5	EB	1733	1755	0.5	Base seeding near SJT, TRW+ to N
62	9/11	1253	1441	2.3	21	NA	29	EB	1305	1441	1.6	Good seeding condts near SJT, TRW+
63	9/13	0508	0845	3.6	18	NA	5	EB	0526	0636	1.2	Seeded developing line, TRW+ at SJT
64	10/6	1023	1141	1.3	19	NA	7	EB	1036	1119	0.7	Fair seeding conditions along front
TOTALS:				132.4		679	1892				62.6	

TABLE 2.

SUMMARY OF OPERATIONAL PROGRAM FLIGHTS
-- San Angelo Project - 1989 Season --

Total number of flights: 64

Total number of flight hours: 132.4

Number of flights with operational treatment: 49

Average duration of flights on which treatment was conducted: 2.27 hours

Number of flights initiated after sunset or before sunrise: 11

Total number of flares used: 1892

Ejectable (EJ):	1550
End-Burning (EB):	342

Average number of flares per seeding flight: 39

Number of cumulus towers treated: 679 (applies only to portions of operational flight when ejectable flares were used)

Average number of flares per treated tower: 2.3 (ejectable flares only)

Average duration of treatment per flight: 1.28 hours

Number of flares used:

Within 25 n.mi. of San Angelo:	1083 (57% of total used)
26 n.mi. to 50 n.mi. from San Angelo:	595 (32% of total used)
More than 50 n.mi. from San Angelo:	214 (11% of total used)

WEATHER MODIFICATION PROGRAM - CITY OF SAN ANGELO

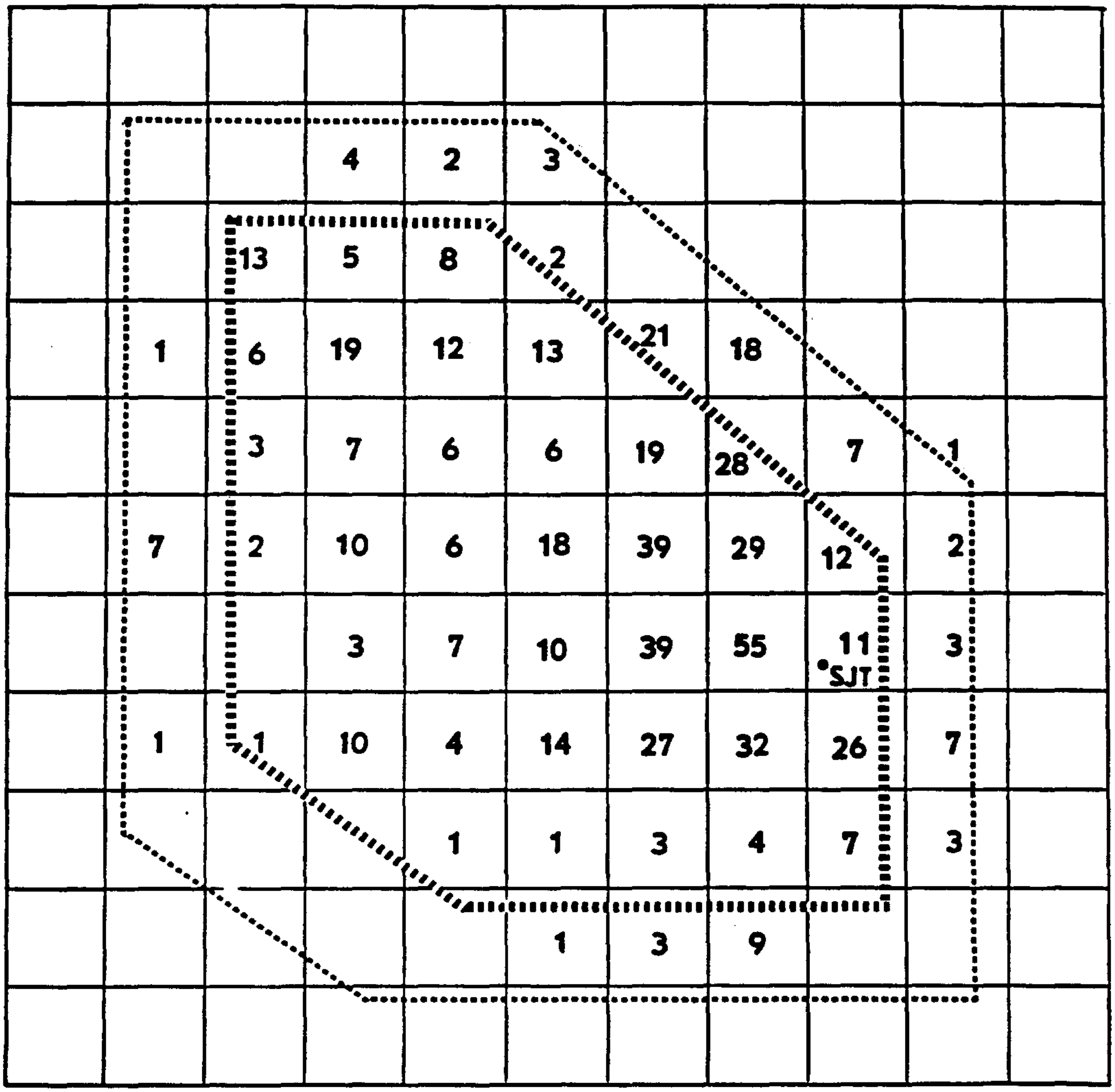


Figure 6. SEEDING EVENTS: 15 APRIL - 15 OCTOBER 1989

A plot of <u>seeding events</u> during the period 15 April through 15 October 1989 is shown, where a seeding event is defined as the activation of at least one ejectable or end-burning flare. Each square is 10 n.m. x 10 n.m. A total of 612 separate seeding events are plotted. The inner six-sided figure is the target area in which rain runoff flows toward the San Angelo reservoirs. The outer six-sided figure is the operational area (which includes the target itself) over which seeding can be conducted. Seeding is not conducted in the region between the operational area and the target, unless it is likely that the subject cloud will move into the target. SJT marks the location of Mathis Field in San Angelo.

Additionally, it is interesting to note the effect that National Weather Service weather warnings had on the operational seeding activity, including warnings for severe thunderstorms, tornadoes and flash floods. In 1989, this effect was minimal. In several cases the warnings were issued well after the seeding activity had been terminated. In cases where warnings were issued at the time seeding was in progress, there were usually other clouds suitable for seeding within the overall San Angelo target but well beyond the warning area.

A listing of the weather warnings issued by the National Weather Service in San Angelo for the period 15 April through 15 October is provided in Table 3. There were 15 days on which one or more warnings were issued. Of these, eight came in May, five in June and one each in April and July. No warnings were issued in August, September and October. May 14th had the most warnings with 14, followed by May 20th and June 10th with 6 each. The lack of warnings in August, September and October is indicative of the rather dry conditions over much of the area during this period.

The suspension criteria under which AI conducted the seeding program are provided in Appendix 11.3.

TABLE 3.

SEVERE WEATHER WARNINGS ISSUED BY
THE NATIONAL WEATHER SERVICE OFFICE IN
SAN ANGELO, TEXAS

15 APRIL THROUGH 15 OCTOBER 1989

Date	Type of Warning	County(ies)	Valid Time of Warning Issue Time (all times CDT)	Valid Until	Comments
4/30	Svr. TRW	Tom Green	1900	2000	Golf-ball size hail
4/30	Svr. TRW	N.Tom Green/S.Coke	2000	2100	Golf-ball size hail
4/30	Svr. TRW	Coke	2130	2230	Walnut-size hail
4/30	Svr. TRW	Runnels	2200	2300	Pea & mrbl size hail
4/30	Svr. TRW	Mason	2300	0000	Golf & bsbl size hail
4/30	Svr. TRW	Menard	1750	0100	Golf ball-size hail
5/01	Svr. TRW	S. Mason	0000	0100	Golf ball-size hail
5/01	Svr. TRW	W. Concho/E. T.Grn.	0214	0315	Hail damage to crops
5/01	Svr. TRW	Concho & Tom Green	0312	0400	3/4 in. hail
5/01	Tornado	W. Kimble	0600	0630	Hook echo, Hondo rdr
5/09	Svr. TRW	Kimble	2130	2230	Pea-size hail
5/12	Svr. TRW	W. Irion	1745	1845	
5/13	Svr. TRW	Tom Green	1217	1300	Funnel cld, lrg hail
5/13	Svr. TRW	Runnels/Tom Green	1315	1415	Hail damage
5/14	Svr. TRW	Sterling	0305	0400	Golf ball-size hail
5/14	Tornado	SW Coke	0329	0430	Tornado on ground
5/14	Tornado	N. T. Green/SW Coke	0429	0530	Tornado on ground
5/14	Svr. TRW	S. Coke	0545	0645	
5/14	Svr. TRW	Tom Green	0545	0645	
5/14	Svr. TRW	Concho	0621	0730	1 in. hail
5/14	Svr. TRW	E. Tom Green	0652	0800	Golf-ball size hail
5/14	Svr. TRW	Central Sterling	0652	0800	
5/14	Flsh Fld	T.Grn/Concho/Runnels	0818	1215	Flooding in counties
5/14	Svr. TRW	Concho	0904	1000	Baseball-size hail
5/14	Svr. TRW	Tom Green	0949	1045	Strng winds & hail
5/14	Svr. TRW	Tom Green	1043	1145	3/4 in. hail at NWS
5/14	Tornado	McCullock	1117	0000	Tornadoes & flooding
5/14	Svr. TRW	Menard	1130	0015	Hail & wind damage
5/15	Svr. TRW	Mason	1207	0115	Damage to buildings
5/16	Svr. TRW	Coke	1226	0115	Golfball-size hail
5/16	Svr. TRW	Coke	1323	1415	Large hail
5/16	Tornado	Menard	1334	1415	Tornado on ground
5/16	Tornado	N. Menard/S. Concho	1426	1515	Hook echo
5/20	Svr. TRW	Concho	1802	1900	Baseball-size hail
5/20	Svr. TRW	E. Runnels	1845	1945	Golfball-size hail
5/20	Svr. TRW	S.Concho/W.McCullock N.Menard	1905	2000	Funnel cloud
5/20	Svr. TRW	McCullock/N.Kimble Mason & Menard	2005	2100	Wind damage
5/20	Svr. TRW	S. Mason/Menard E. Schleicher	2105	2200	Strong winds
5/20	Svr. TRW	Schleicher	2203	2300	3/4 in. hail
6/4	Svr. TRW	Reagan	2027	2130	
6/4	Svr. TRW	Coke	2202	2300	
6/4	Svr. TRW	Runnels	2300	0000	

TABLE 3 (Cont.)

SEVERE WEATHER WARNINGS ISSUED BY
THE NATIONAL WEATHER SERVICE OFFICE IN
SAN ANGELO, TEXAS

15 APRIL THROUGH 15 OCTOBER 1989

Date	Type of Warning	County(ies)	Valid Time of Warning Issue Time (all times CDT)	Valid Until	Comments
6/6	Svr. TRW	Sterling	1744	1845	Hen's egg-size hail
6/7	Svr. TRW	NE. McCullock	2210	2315	Marble-size hail
6/10	Svr. TRW	N. Tom Green	1412	1515	Golfball-size hail
6/10	Svr. TRW	W.& N.Cntrl Coke	1543	1645	
6/10	Svr. TRW	N.Cntrl Coke	1715	1815	Golfball-size hail
6/10	Svr. TRW	N.Cntrl Runnels	1730	830	Golfball-size hail
6/10	Svr. TRW	Sterling	1815	1915	Strong winds
6/10	Svr. TRW	T. Green/Sterling Runnels	1845	1945	Strong winds
6/13	Svr. TRW	SW Reagan/Crockett	1905	2000	
6/13	Svr. TRW	W. Crockett	1954	2045	
7/4	Svr. TRW	E. Crockett	1408	1500	

5.0 ASSESSMENT OF THE SEEDING EFFECT

roach

Evaluating the effect of seeding in an operational program is essential if the effort is to have long-term credibility. This is not an easy task! In scientific experiments there is a requirement to provide treatment on a random basis. In operational programs designed to produce maximum effect, there are no non-seeded control days set aside to serve as an objective basis for comparison with the days that have been seeded. However, it is possible to make an assessment of the effect of seeding using target-control regressions that have been derived from historical rainfall records. Flueck (1976) outlines this procedure and discusses its advantages and limitations. The basic requirements are that rainfall in the target and control areas be reasonably correlated and that rainfall at the control stations not be contaminated by seeding in the target.

Following is our preliminary assessment of the effectiveness of seeding during each season of the total 5-year program. A more comprehensive assessment is in progress which includes extensive data checking and re-calculations. This should be available as an independent report by 31 December 1989.

Our approach to the assessment of seeding effects is similar to several past evaluations of seeding programs conducted by AI over the past 30 years. Historical monthly precipitation data were accumulated for long-term rainfall stations within the target and outside to the west and south. From those data a base period from 1960 through 1984 prior to seeding was selected. The stations are shown in Figure 7. Six control stations (Midland Airport, Penwell, McCamey, Bakersfield, Ozona and Sonora) and nine target stations (Garden City, Sterling City, Cope Ranch, Water Valley, Water Valley 10 NE, Funk Ranch, San Angelo, Eldorado, and Mertzon and/or Mertzon 10 NE were used in the analysis. Sheffield, Texas, was considered as a control station, but its record had too many gaps to permit its use.

Having selected the target and control stations, the analysis proceeded in the following steps:

- A linear regression relationship between the base period average seasonal (May through September) target and control rainfalls was derived. In a variation of this basic analysis, regression equations between mean seasonal control rainfall and the total seasonal rainfall for each target station were derived. This analysis produced ten separate equations, one for the overall target and one each for the nine target stations.

- The regression equations were then used to evaluate the five years of seeding. The 1989 measured mean May-September rainfall for the six control stations was substituted into the regression equations, and the overall target rainfall and the rainfall for each station was predicted.

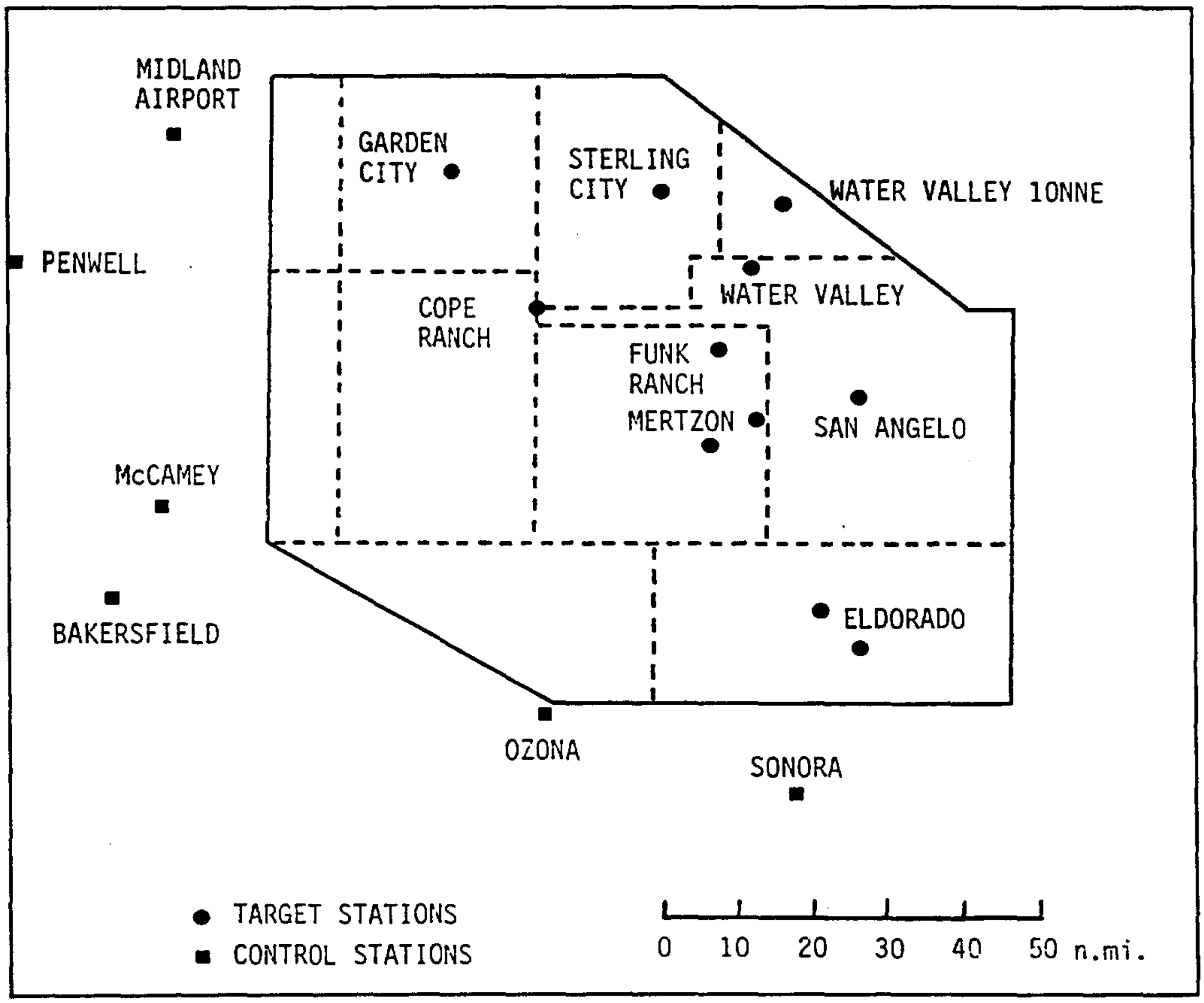


FIGURE 7. Locations of target and control raingages within and near the San Angelo watershed.

- The predicted rainfalls were compared with the rainfalls actually measured during the operational periods to obtain an estimate of the seeding effect. This was accomplished for each year and for all five years of the program.

Any evaluation is only as good as the input data so the quality of the raingage records had to be addressed before this analysis could begin. All rainfall observations, except for those from the Mertzon 10 NE station, were provided by the National Climate Data Center in Asheville, North Carolina. Overall, the station record is fairly complete, but missing records were a problem for some stations. Table 4 lists the data availability for the target and control stations for the base period (1960 through 1984) and for the project period (1985 through 1989). The data are based on the number of station-months that were edited. Each station-month requiring any intervention is included, whether one day or the entire month was edited.

Table 4.

NUMBER OF STATION-MONTHS* EDITING NECESSARY PRIOR TO REGRESSION ANALYSIS

Station	Base Period (1960-1984;125 mos)	Project Period (1985-1989;25 mos)
Control Stations		
Midland	0	0
Penwell	6	0
McCamey	6	0
Bakersfield	1	0
Sheffield	17 (excluded)	2 (excluded)
Ozona	3	0
Sonora	0	3
Target Stations		
Garden City	1	0
Sterling City	4	5
Water Vly	0	0
Water Vly 10NNE	4	1
Cope Ranch	0	0
Funk Ranch	3	0
San Angelo	0	0
Mertzon	9	1 (record ends in 1987)
Mertzon 10 NE	-	0 (1987 through 1989)
Eldorado**	2	0

* A station is said to have one station-month of editing, whether one day of record or the entire month was edited.

** The record for Eldorado included Eldorado 11NW from 1960 through most of 1981 and Eldorado 2SE from September 1981 through the project period.

A study of Table 4 reveals that three stations (San Angelo, Water Valley and Midland) had a perfect record. With the exception of Sheffield (and perhaps Mertzon), the interpolations for missing data were minimal for the other stations. Sheffield was dropped from consideration after studying its record. Mertzon appeared to be acceptable.

Using the values from Table 4, the magnitude of the editing can be summarized as follows. Of the 1,875 total station months in the base period (with Sheffield excluded), 39 (2.1%) required editing. For the project period, 10 of the 400 station months (2.5%) were adjusted. Those values are overestimates because in many instances the missing data periods were only a matter of days. The real percentages, based upon daily records, are considerably lower. However, even the Table 4-based values fall within acceptable limits regarding the completeness and quality of the input data.

All editing necessary to complete the study with the remaining stations will be published in an appendix of the more comprehensive study after all data checking has been completed.

In the cases of Eldorado and Mertzon, the gage sites were moved during the report period. Eldorado had no overlapping record for the two sites. The records for Mertzon and Mertzon 10NE overlapped from 1977 through 1986 so it was possible to determine the relationship between the two stations. Preliminary results indicate that the rain measurements at the new Mertzon site (i.e. Mertzon 10NE) are systematically low relative to the old site. Use of this site for a portion of the treatment period will tend to underestimate the effect of seeding.

A listing of the data used for this preliminary analysis of seeding effect appears in Table 5. A revised table will appear in the reanalysis after data checking has been completed, so interested parties can verify our calculations, assess the conclusions we have reached based on the basic data set, and apply other analysis methods if desired.

TABLE 5.

MAY TO SEPTEMBER YEARLY RAINFALLS FOR CONTROL AND TARGET STATIONS

	Control Stations							Target Stations									
Yr	MAF	Penwell	McCamey	Bakersfield	Ozona	Sonora	Mean	Garden City	Sterling City	Water Valley	Water Valley 10NNE	Cope Ranch	Funk Ranch	SJT	Eldorado	Mertzon	Mean
							Pre-Treatment Period										
60	7.81	7.86	8.21	6.90	7.09	5.13	7.17	8.17	6.53	6.20	5.43	6.21	7.19	5.24	5.23	4.98	6.14
61	15.65	5.21	5.65	3.82	13.98	11.97	9.38	17.33	16.42	12.01	18.45	12.21	16.52	13.23	17.84	17.77	15.75
62	10.81	9.74	5.55	6.66	4.94	12.43	8.36	9.45	8.35	4.91	4.03	6.83	6.87	5.40	9.00	6.16	6.77
63	8.03	6.01	6.17	6.66	6.55	8.47	6.98	8.70	8.52	7.75	9.97	10.20	8.91	9.37	7.87	8.78	8.89
64	5.55	3.83	12.23	5.67	9.17	16.29	8.79	9.78	13.58	8.53	8.34	9.38	7.47	5.19	9.19	8.51	8.88
65	8.01	7.04	8.35	6.08	9.34	9.57	8.07	10.75	14.73	11.09	14.89	14.40	9.91	9.82	7.86	8.01	11.27
66	12.60	9.57	8.33	11.12	12.72	10.21	10.76	6.53	11.70	13.13	11.76	11.52	15.72	10.42	14.68	11.82	11.92
67	5.13	8.27	6.74	6.90	7.39	12.26	7.78	10.96	13.93	13.13	12.48	16.01	13.37	13.55	12.52	13.42	13.28
68	10.48	8.67	11.29	9.82	12.26	10.33	10.48	11.07	9.04	9.96	9.85	5.91	12.02	11.60	10.33	9.41	9.91
69	8.55	5.47	7.41	8.08	10.92	8.26	8.12	12.00	15.86	15.23	11.80	7.12	14.48	12.78	10.34	9.44	12.12
70	4.27	5.03	8.65	10.66	6.19	8.73	7.26	9.02	6.38	7.07	9.63	8.07	8.11	6.97	9.81	7.86	8.10
71	10.45	11.07	7.06	8.84	22.75	18.73	13.15	14.01	15.84	19.19	19.90	11.01	17.12	16.70	16.77	22.18	16.97
72	8.33	11.44	11.15	11.14	19.62	20.99	13.78	14.84	17.22	16.06	20.38	14.64	16.20	18.23	13.65	14.47	16.19
73	5.02	6.31	5.42	10.37	10.69	11.23	8.17	6.53	6.95	12.03	13.62	7.72	15.00	9.82	11.11	9.65	10.27
74	11.94	12.11	18.38	29.73	20.83	23.30	19.38	13.26	16.41	18.20	20.80	17.41	19.24	15.01	22.12	17.62	17.79
75	18.34	13.26	11.13	11.70	9.48	14.10	13.00	16.39	15.50	15.21	13.91	15.87	11.76	12.87	10.96	1.51	13.89
76	8.87	8.90	11.37	16.94	17.10	24.08	14.54	16.80	14.74	14.60	12.52	18.17	12.33	11.76	19.38	12.41	14.75
77	2.27	4.39	4.79	3.94	5.85	7.03	4.71	6.95	7.01	10.28	10.06	10.49	6.22	3.78	6.29	5.11	7.36
78	11.66	10.06	15.70	15.29	9.10	15.94	12.96	9.35	12.70	13.79	11.17	14.19	8.10	9.33	15.37	10.27	11.59
79	9.42	7.23	5.85	7.31	8.96	8.77	7.92	12.49	6.85	9.24	9.83	12.54	10.48	6.36	9.36	7.54	9.41
80	14.07	13.30	10.23	8.56	11.94	14.00	12.02	19.05	17.43	22.58	17.42	14.15	20.01	22.49	13.07	17.20	18.16
81	8.08	5.39	7.01	7.29	10.61	13.95	8.72	9.27	11.75	11.56	11.50	11.01	9.42	13.30	8.25	16.14	11.46
82	9.95	7.58	2.73	7.47	6.88	8.56	7.20	10.51	14.89	17.83	18.08	10.716	9.18	11.08	8.26	16.11	12.96
83	1.74	2.15	1.72	2.05	5.01	6.13	3.13	2.19	5.84	7.43	7.84	5.28	5.34	5.45	5.97	9.30	6.07
84	10.73	11.43	8.03	7.63	5.53	6.06	8.24	7.59	5.28	6.12	5.31	5.31	8.77	7.21	7.57	9.92	7.01
							Treatment Period										
85	8.08	7.29	10.10	7.20	15.63	11.81	10.00	13.58	11.82	9.70	8.86	10.70	12.39	12.54	12.02	22.08	12.63
86	19.49	17.36	12.88	7.07	13.88	18.67	14.89	13.90	17.99	20.26	28.65	31.34	15.92	21.135	15.65	18.00	20.34
87	9.32	12.49	9.99	15.00	13.50	15.37	12.61	11.02	16.05	20.30	21.51	10.40	14.37	20.51	17.63	13.29*	16.12
88	16.49	10.83	7.88	8.41	15.30	12.15	11.84	18.13	15.79	13.35	12.78	14.11	12.57	10.79	15.26	24.49*	15.25
89	5.87	6.65	5.29	5.91	3.39	3.95	5.18	10.14	7.70	13.19	13.51	3.67	7.33	9.84	7.70	11.19*	9.36

* The gage totals for 1987 through 1989 are from Mertzon 10NE

5.2 Results

A listing of the regression equations relating target to control rainfalls and the resulting correlation coefficients are presented in Table 6. Note that the correlations run from a maximum of 0.84 to a minimum of 0.58. The overall target vs control correlation is 0.76. A complete correlation matrix among all stations was prepared which shows the relationship between each station and each of the other stations. For those stations with adequate records, the correlation coefficients range from about 0.3 to 0.9. Given these correlations the control stations are rather crude predictors of the total and individual target station rainfalls. Actually, it is surprising the correlations are this strong given the extreme variability of summer convective rainfall between stations in west Texas.

It must be emphasized that no search was made to find the "best" stations or "best grouping of stations" for this analysis. Such a search requires a physical basis, and we could find no physical reason to modify our initial selection of stations. In truth, we have used all of the candidate control stations that had a long-term rainfall record. In the case of the target stations, we used all stations within the target that had a complete or nearly complete record for the period of analysis.

TABLE 6.

REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS
RELATING TARGET TO CONTROL RAINFALLS
FOR THE SAN ANGELO RAIN ENHANCEMENT PROGRAM
(Period of Record 1960 through 1984)

	Correlation Coefficient	Equation
Control vs Target	0.76	$T_R = 3.66 + 0.814C_R$
Control vs Garden City	0.64	$G_R = 3.90 + 0.731C_R$
Control vs Sterling City	0.64	$S_R = 4.29 + 0.775C_R$
Control vs Cope Ranch	0.66	$C_R = 4.04 + 0.734C_R$
Control vs Water Valley	0.63	$(WV)_R = 4.20 + 0.825C_R$
Control vs Water Valley 10NNE	0.59	$(WV')_R = 4.62 + 0.806C_R$
Control vs Funk Ranch	0.67	$F_R = 3.74 + 0.818C_R$
Control vs San Angelo	0.63	$(SA)_R = 2.73 + 0.828C_R$
Control vs Mertzon	0.58	$M_R = 4.40 + 0.736C_R$
Control vs Eldorado	0.84	$E_R = 1.08 + 1.060C_R$

The equations of Table 6 were used to predict the overall target rainfalls and the rainfall at each target station for each of the five years of seeding operation. The results in terms of observed to predicted rainfall ratios are presented in Table 7 and in terms of differences between observed and predicted rainfall are presented in Table 8. If seeding has increased the rainfall during the program, a large number of individual ratios and differences will be greater than 1.

TABLE 7.

RATIOS OF OBSERVED TO PREDICTED RAINFALLS FOR TARGET STATIONS BY YEAR AND FOR ALL FIVE YEARS OF OPERATIONAL SEEDING

Station	1985	1986	1987	1988	1989	All Years
Grdn Cty	1.21	0.94	0.84	1.44	1.32	1.13
Strlng Cty	0.98	1.14	1.14	1.17	0.93	1.09
Wtr Vly	0.78	1.23	1.39	0.96	1.56	1.16
Wtr Vly 10NNE	0.70	1.72	1.32	0.90	1.54	1.24
Cope Ranch	0.94	2.09	0.79	1.11	0.47	1.17
Funk Ranch	1.04	1.00	1.02	0.94	0.92	0.99
San Angelo	1.14	1.42	1.56	0.86	1.40	1.28
Mertzon	1.88	1.17	0.97	1.87	1.36	1.43
Eldorado	1.03	0.93	1.22	1.12	1.17	1.08
Target	1.07	1.29	1.16	1.15	1.19	1.18

TABLE 8

DIFFERENCES BETWEEN OBSERVED AND PREDICTED RAINFALLS
FOR TARGET STATIONS BY YEAR AND FOR
ALL FIVE YEARS OF OPERATIONAL SEEDING
(Units are inches)

Station	1985	1986	1987	1988	1989	All Years (avg.value)
Grdn Cty	2.37	-0.88	-2.09	5.57	2.45	1.48
Strlng Cty	-0.22	2.16	1.99	2.32	-0.60	1.13
Wtr Vly	-2.75	3.78	5.70	-0.62	4.72	2.17
Wtr Vly 10NNE	-3.82	12.03	5.12	-1.38	4.71	3.33
Cope Ranch	-0.68	16.37	-2.90	1.38	-4.17	2.00
Funk Ranch	0.47	0.00	0.32	-0.86	-0.65	-0.14
San Angelo	1.53	6.29	7.34	-1.74	2.82	3.25
Mertzon	10.32	2.64	-0.39	11.38	2.98	5.39
Eldorado	0.34	-1.21	3.19	1.63	1.13	1.02
Target Avg.	**0.83**	**4.56**	**2.20**	**1.96**	**1.48**	**2.21**

The real challenge is interpreting the results of Tables 7 and 8. The regression equations for individual stations have correlations that range between 0.84 and 0.58, so they are not perfect predictors of target rainfall. It would be a mistake to interpret the results of Tables 7 and 8 as "proving beyond all doubt" that seeding increased the rainfall at a particular station in a particular year. However, it is interesting to note that the 19% apparent seeding effect in 1989 across the overall target (Table 7) is greater than in any of the other project years except 1986. The fact that such a strong apparent increase occurred in a dry year is particularly worthy of note.

Overall impressions may have considerable validity. Approaching the results in this way, one immediately notes there is a large number of ratios greater than 1. This is especially true in 1989 for the stations closest to San Angelo (i.e. San Angelo and Mertzon), where most of the seeding took place and for all years combined. The target variable has ratios greater than 1 for the five combined years of operation. This is important!!

These overall results certainly suggest a positive effect from seeding that may amount to an average of +18% for the target during all years of operation. The probability of five consecutive seasons showing positive values due to chance is only 3%. In addition, the area closest to San Angelo had apparent overall effects ranging between 28% and 43%. The mean increases in rainfall for this region closest to the San Angelo reservoirs average between 3 and 5 inches per season (May through September).

Plots of results noted in Tables 7 and 8 are provided in Figures 8 and 9. The obvious "clinker" in the results are the ratio and rain-difference values for Funk Ranch. No effect, either positive or negative, is indicated at this site, even though the stations around it suggest appreciable effects from seeding. At this time, we have no explanation for this result other than a possible anomaly due to character of summer cumulus rainfall. To increase the confidence in these results, the complete re-analysis of the data will include extensive sensitivity testing. If the apparent effect holds firm after this testing, it will greatly strengthen the case for seeding.

Along these lines, it is interesting to note that the treatment period is wetter within the overall target than the previous five-year periods (i.e. 1960-1964, 1965-1969, 1970-1974, 1975-1979, 1980-1984). This may also represent an effect of seeding. An alternative argument might be that the weather was becoming progressively wetter over the 30 years since 1960 in the San Angelo target, and that natural changes account for the apparent effect of seeding. However, there is no current evidence to support this alternative argument.

In the more comprehensive independent analysis presently underway, the following will be addressed:

- Complete checking of the basic data set.
- Rederivation of the results that have been presented in this Final Report.
- Presentation of results as of percentages of station normals.
- Derivation of a regression relationship between Mertzon and Mertzon 10NE, in order to quantify the impact of using Mertzon 10NE in place of Mertzon for the years 1987, 1988 and 1989.
- Additional significance testing to determine the probability that the apparent effects of seeding are not due to chance.
- Development of a relationship between the area of greatest apparent seeding effect and the area where most of the seeding was conducted.