A REVIEW OF THE EDWARDS AQUIFER PRECIPITATION ENHANCEMENT PROGRAM

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Abstract The organization and facilities of the Edwards Aquifer Precipitation Enhancement Project (EAPEP) is reviewed, and the resources applied in the 1999, 2000, and 2001 seasons are summarized. A preliminary evaluation of the 1999 and 2000 project seasons suggests a 24% increase in rainfall volume for floating target units of 1,964 km$^2$ that actually received treatment within the Edwards Aquifer fixed target. This corresponds to an average water increment of 626 acre-feet per unit. The full effect of seeding over the entire target area is presently unknown. The current estimate of the benefit-to-cost ratio is 9:1.

1. INTRODUCTION

The Edwards Aquifer plays an integral role in providing South Central Texas with the priceless resource of water. It is the sole provider of water to the residents of San Antonio, and the also contributes significantly to agriculture and industry. The Edwards Aquifer region receives an average of between 25 to 35 inches of precipitation annually. Approximately half of the annual precipitation occurs between May 1 and September 30, when cloud seeding operations are normally conducted.

The Edwards Aquifer Authority (EAA), established in 1995 by the Texas Legislature, replaced the Edwards Underground Water District, which had been established in 1959. In an effort to conserve and efficiently manage the Edwards Aquifer, the EAA has sought out additional methods of water resource management, such as rain augmentation. In 1999, the EAA contracted with Weather Modification, Inc. (WMI) to conduct the Edwards Aquifer Precipitation Enhancement Project.
Program (EAPEP). The EAPEP is funded jointly by the EAA and the Texas Department of Agriculture, with the sole intent to enhance precipitation through cloud seeding. The EAPEP target area, shown in Figure 1, covers 22,015 km$^2$ within 12 counties in south central Texas.

2. SEEDING METHODOLOGY

The seeding methodology for the EAPEP has been adapted from similar weather modification programs conducted by WMI in North Dakota, Oklahoma, and elsewhere in Texas. These methods and techniques have been developed, reviewed, and refined over a period of years, as described by Sedlock et al. 2002. Precipitation efficiency is defined as "the percentage of condensed water within a cloud system that reaches the ground as precipitation" (Kahan et al., 1995). Increasing the precipitation efficiency requires methodology that brings as much suspended liquid water as possible to the ground. The EAPEP is designed to increase the precipitation through the glaciogenic seeding of ice-free, supercooled cumulus congestus. The ice-phase is thus initiated earlier than would naturally occur, providing a head start in precipitation development. WMI used silver iodide-complex flares manufactured by Ice Crystal Engineering, LLC (ICE) on the EAPEP, and wing-tip ice nuclei generators which burn a silver iodide-complex acetone solution. Both produce nuclei that function predominantly by the condensation-freezing mechanism. Each ejectable flare contains 20 g of seeding agent, falls approximately 4,000 feet (relative to the surrounding air), and burns for approximately 37 seconds. The ice nucleating effectiveness of the flares manufactured by ICE is documented (DeMott, 1999).

The formulation of seeding solution used for base seeding on the EAPEP was tested at CSU in February 1997. A 1-mole solution of Ag$_{1.8}$Cl$_{0.2}$ - NaCl was found to produce $10^{11}$ ice nuclei per gram AgI burned, active at $-6^\circ$C (DeMott, 1997).

3. PROGRAM ELEMENTS

3.1 Personnel

The EAA contracted with WMI to provide all operational personnel for the project. This included the pilot for each aircraft, a meteorologist for the field office, and a technician for the installation, maintenance, and calibration of the radar and field office equipment. All pilots held multi-engine and instrument ratings, were current in their aircraft, and had received training on weather modification operations prior to the start of each season. Though not required to do so by contract, WMI also provided first officers (co-pilots) for the project aircraft much of the time, to lessen the cockpit workload, and also to further their training. The meteorologist acted as the primary liaison between WMI and the EAA. The technician maintained the radar and all electronic equipment used in the field operations facility. A schematic of the operational elements for the EAPEP is shown in Figure 2.

3.2 Field Operations Facility

The field office facility, shown in Figure 3, was located at the Hondo Municipal Airport in Hondo, a short distance west of San Antonio. This was done for several reasons. The radar and aircraft were thus based within the target area, but far enough west to afford some upwind radar coverage. The aircraft were also based at Hondo for much of the period. Air traffic volume from San Antonio itself is great enough that prompt dispatch of seeding aircraft could not always be ensured. In addition, the EAA
operates a field office in Hondo, so daily interaction was possible.

Figure 3. Field Office Facility and Radar, located at Hondo, Texas. The radar tower and radome are the property of the City of Hondo, and were former National Weather Service facilities. The radar antenna within the radome, and the radar itself, are the property of WMI. In October 2001, after the project season had concluded, a tornado struck the airport and the radome was damaged (see inset). It has since been repaired.

All seeding operations were directed from the field operations facility. The air-conditioned facility, a customized WMI trailer, contained the on-site weather radar, aircraft tracking system, project computers, Internet access, and VHF (aircraft) communications equipment. It was properly anchored to protect against high winds. As is standard WMI procedure, the facility was also equipped with a gasoline-fueled auxiliary power unit to provide electricity should the local commercial power fail.

3.3 Weather Radar

The project weather radar was located on a radar tower previously used by the National Weather Service in Hondo (see Figure 3). The radar is an Enterprise Electronics Corporation WSR-74C, C-band radar with a 2.44 m diameter antenna. The radar system is interfaced with a computerized color radar display with recording capability. The radar is capable of detecting clouds producing rainfall at a rate of 1 mm hr⁻¹, at a range of 70 NM. The overall radar data system is officially known as the Real-time Analysis and Prediction System (RAPS). It consists of a video processor and an angle interface that work together with computer software for the acquisition of raw radar video data. The video processor and angle interface reside in a dedicated PC computer with an oversize 20-inch color display. The software runs in an X-windows environment on a Linux operating system. The data are manipulated by TITAN (Thunderstorm Identification, Tracking, Analysis, and Now-casting, Dixon and Wiener 1993). TITAN is capable of many different real-time analysis operations.

3.4 Aircraft

Cloud seeding was conducted using two Cessna 340 aircraft, each equipped with ejectable flare racks and acetone burners. The Cessna 340 aircraft is a pressurized, twin-engine, six cylinder, turbo-charged, fuel-injected, all weather aircraft (Figure 4). Both aircraft were equipped with weather avoidance radar and global navigation system (GPS) receiver. The maximum service ceiling is near 29,000 feet. Flight endurance is on the order of 5 hours, if needed. The aircraft are capable of safe flight in all types of weather, day and night. The Cessna 340's indicated air speed for cloud penetrations is typically 155 knots. The nominal rate of climb is 1000 ft min⁻¹. Each aircraft carried 204 20 g ejectable silver iodide flares, and two seven-gallon acetone burners. The aircraft were based at the Hondo Municipal Airport.

Figure 4. One of WMI's Cessna 340 cloud seeding aircraft, rigged for operations. The silver canister beneath the wing is an ice nucleus generator that burns a silver iodide complex solution for seeding at cloud base. Cloud top seeding was done with ejectable flares, fired from a belly-mounted rack.

In early August of 2001, a hangar fire at Hondo destroyed one of the WMI aircraft (and numerous others), and all seeding agent reserves. Within two days, WMI had another operational seeding aircraft on the project, and had replenished
the seeding agent reserves. At that time, both aircraft were moved to the Castroville Airport for the duration of the 2001 season, where FBO services could still be obtained.

3.5 Aircraft Flight Tracking

The Field Office Facility was equipped to receive and record data from the aircraft GPS-based AirLink tracking system. The GPS system displays the exact position of each aircraft superimposed on the radar CAPPI display to enable the meteorologist to accurately direct the seeding aircraft to optimum seeding locations within the storm system. AirLink is a Windows-based program that also displays the seeding events, in real-time, i.e. the exact times and locations of flare drops and total time and location of the acetone generator usage. The AirLink system can simultaneously display up to five aircraft, and can also use World Aeronautical Charts and other maps as a background display. The map backgrounds enable the meteorologist to pinpoint the aircraft's position with respect to the radio navigational aids.

4. DAILY OPERATIONS

Successful rain enhancement programs require procedures and routines that can be easily repeated, to ensure consistently favorable results. WMI has honed its operational procedures during numerous weather modification projects throughout North America, and continues to update them as new information becomes available.

Each day began (in the absence of workable clouds) with the project meteorologist preparing a detailed weather forecast, which was then communicated to the project pilots. The forecast was developed using real time weather information obtained from the Internet, and from local and regional observations, including those of the project radar. A single number, referred to as the "convective day category", or CDC, then subjectively summarized the detailed forecast. This technique was developed for the Alberta Hail Suppression Project by Strong (1979) and gives the cloud conditions and possibility of seeding activity for the day. The more positive CDC values indicate an increasing probability of precipitation enhancement seeding opportunities. For precipitation enhancement programs like the EAPEP, the daily CDC values are interpreted as shown in Table 1. The interested reader may wish to compare Table 1 with the analogous CDC table in Sedlock et al. (2002), a hail-suppression program.

Each flight crew was then assigned either weather-watch, standby, or alert status.

- **Weather Watch.** Development of convection unlikely. Pilots are free to do as they wished but still required to carry their cellular phone or pager.
- **Standby.** Convective development is thought likely later in the day. Clouds, if developing, are

<table>
<thead>
<tr>
<th>CDC</th>
<th>Strategy</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>-3</td>
<td>No Seed</td>
<td>Clear skies, cumulus humilis, or stratus (with no rain). No deep convection.</td>
</tr>
<tr>
<td>-2</td>
<td>No Seed</td>
<td>Overcast stratus-producing rain for prolonged periods.</td>
</tr>
<tr>
<td>-1</td>
<td>No Seed</td>
<td>Broken to overcast low and middle cloud (cumulus clouds with tops warmer than -5°C) producing some weak rain showers, but without seedable targets.</td>
</tr>
<tr>
<td>0</td>
<td>Seeding Unlikely</td>
<td>Cumulus clouds with tops warmer than -5°C.</td>
</tr>
<tr>
<td>+1</td>
<td>Possible Seeding</td>
<td>Towering cumulus with tops colder than −5°C, but generally weak, and not conducive to seeding.</td>
</tr>
<tr>
<td>+2</td>
<td>Seed</td>
<td>Towering cumulus clouds with tops colder than −5°C, longer-lived and likely conducive to seeding.</td>
</tr>
<tr>
<td>+3</td>
<td>Seed</td>
<td>Mesoscale convective complexes, well-organized multicell storms, or linear storms. New growth (flanking cumulus congestus) conducive to seeding.</td>
</tr>
<tr>
<td>+4</td>
<td>Seed</td>
<td>Deep convection (cumulonimbus) with hail potential. New growth (flanking cumulus congestus) conducive to seeding.</td>
</tr>
<tr>
<td>+5</td>
<td>Seed Unless Suspended</td>
<td>Deep convection generally containing hail and/or forming into well organized squall lines with a threat of severe weather.</td>
</tr>
</tbody>
</table>
not close to being seedable yet. Aircraft are able to launch and reach a target cloud within 30 miles of the airport 45 minutes after the request to launch has been made by the meteorologist.

- **Alert.** Seedable clouds are imminent. Aircraft are able to launch and reach target cloud within 30 miles of the airport in 25 minutes after the request to launch has been made by the meteorologist.

The WMI EAPEP radar operated 24 hours a day, seven days a week, and the meteorologist monitored the radar display whenever the potential for convection existed. Other meteorological data sources such as satellite and NWS radar images, commercial radio and television broadcasts, NOAA weather radio, and persistent sky watching were used to maintain surveillance. The criteria used to initiate operations included the following:

- **CDC.** A large positive CDC (indicative of a very unstable atmosphere) necessitated launching aircraft at the first sign of convection.

- **Available Light.** Cloud seeding for rainfall enhancement requires the pilots to visually select which cumulus turret they are to seed. Night operations were conducted whenever there was enough available light, whether that light was provided by the moon or by the storm's own lightning.

- **Cloud Base.** Cloud seeding is ineffective if the precipitation falling from a cloud evaporates before it reaches the ground. Clouds with bases less than 12,000 ft above ground level (agl) were deemed seedable.

- **Cloud Top.** The top of the cloud must pass through the \(-5^\circ C\) level for the glaciogenic seeding agent to be effective. Clouds with tops warmer than approximately \(-5^\circ C\) were not seeded.

- **Severe Weather.** Thunderstorms were deemed severe, and thus off limits for seeding, when warnings were issued by the NWS, or if hail or tornadic activity was observed by project personnel. The EAPEP does not seed severe thunderstorms.

- **Storm Characteristics.** Visual characteristics were often enough to initiate or negate a launch. Factors negating launches included severe shear, or dissipation of the storm cloud. Factors initiating launch included explosive cloud growth and well-defined storm characteristics.

The meteorologist launched aircraft whenever the seeding criteria were met. An aircraft were launched on patrol (reconnaissance) when some criteria were met, or when the meteorologist determined that clouds would likely soon be seedable. The number of aircraft airborne at one time depended on the project area cloud coverage. The meteorologist timed launches so that both aircraft would not need to return for fuel and seeding agent simultaneously. This strategy ensured that at least one aircraft would be seeding clouds at all times seedable clouds were present. The meteorologist terminated seeding operations when suitable activity dissipated and no new growth was observed or expected, short-term. Another basis for termination of seeding operations was the potential for severe weather or flooding. Project seeding suspension criteria were developed to avoid treatment of hazardous clouds. These criteria were:

- Tornado or funnel-bearing clouds.
- Stationary and very slow-moving storms.
- Any perceived flood potential, regardless of source.
- NWS Flood warning.
- Edwards Aquifer Authority discretion.

5. **PROGRAM SUMMARY**

Radar and aircraft data files have been archived and provided to the Edwards Aquifer Authority, as required by Texas regulations. The meteorologist also kept detailed operations logs, which aid in the completion of storm summaries, and in the documentation of operational practices and decisions.

The EAPEP began operations in 1999, and continued through 2001. The 1999 season ran from 15 April through 15 September; the 2000 season began 1 March and continued through 30 November, and the 2001 season started on 15 April, and concluded of 15 September. Table 2 summarizes the data from the three seasons. The reasons for the apparent decrease in seeding have not been fully established. Possible explanations include natural variations in the number of opportunities, increased severe weather (which might have resulted in more...
frequent seeding suspensions), increased air traffic (and thus increased air traffic control limitations) near San Antonio, and changes in personnel. The last could be a factor only if some were more aggressive than others.

**TABLE 2. Seasonal Seeding Summary**

<table>
<thead>
<tr>
<th>Season</th>
<th>Flight Hours</th>
<th>Ejectable Flares</th>
<th>Generator Hours</th>
<th>Total Seeding Agent (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>175</td>
<td>1,826</td>
<td>6.1</td>
<td>37,400</td>
</tr>
<tr>
<td>2000</td>
<td>219</td>
<td>1,444</td>
<td>44.2</td>
<td>29,300</td>
</tr>
<tr>
<td>2001</td>
<td>153</td>
<td>834</td>
<td>24.5</td>
<td>21,700</td>
</tr>
<tr>
<td>TOTAL</td>
<td>547</td>
<td>3,804</td>
<td>74.8</td>
<td>88,400</td>
</tr>
</tbody>
</table>

Equipment down-time was definitely not a factor, as the project equipment functioned well, and was rarely out of service in any of the three seasons. Even when an aircraft and the seeding agent reserves were lost in a hangar fire during the 2001 season, a replacement aircraft was on station and in operation within two days.

6. EVALUATION

In the spring of 2001, the Edwards Aquifer Authority contracted with Woodley Weather Consultants (WWC), of Littleton, Colorado, for an independent evaluation of the 1999 and 2000 EAPEP programs. A preliminary evaluation based upon NWS radar data is presented herein, courtesy of WWC. Complete details of the new methodology developed by WWC will be provided in a paper to be submitted for publication in the *Bulletin of the American Meteorological Society*.

The method developed by WWC is significantly different from others presently being applied to the evaluation of Texas programs, as it ostensibly offers a viable means to objectively and comprehensively evaluate operational cloud seeding programs on an area basis. The new procedures have been applied by WWC to the High Plains Underground Water Conservation District and EAPEP for the 1999 and 2000 seasons, under separate contracts with those program sponsors.

6.1 Method

The new method, developed by Dr. William Woodley and Dr. Daniel Rosenfeld (Woodley and Rosenfeld 2002, hereafter WR), makes use of NWS WSR-88D (NEXRAD) 15-minute mosaic reflectivity data for all of Texas in estimating rainfall for the “analysis units”, using a reflectivity, \( Z \), to rainfall rate, \( R \), relationship of:

\[ Z = 300 R^{1.4} \]

as determined by Woodley et al. (1975). This relationship is presently employed by the NWS as the standard for rainfall estimation by radar. In working with the NEXRAD data, Woodley et al. (2001) have shown that this \( Z-R \) relationship provides good agreement with the rain measurements from a dense network of non-recording rain gauges read on a monthly basis.

Each analysis unit is defined by a circle having a radius of 25 km (covering 1,964 km²), centered on an echo when it first reaches 40 dBZ. A second unit is defined when another echo reaches 40 dBZ at least 25 km from the first unit. Thus, by design some units may overlap in order to make certain that no echo escapes analysis. Radar-estimated rainfalls are determined for all units going back in time from unit definition, to the time the echo first appeared in the unit, and then forward in time until all echo disappeared from the unit. All units move at the direction and speed of radar echoes in and around the unit, as determined by an objective computer algorithm.

After the units on each day have been defined, the position and seeding actions of all project aircraft within Texas as a function of time are superimposed onto the unit maps. A seeding unit is one in which some silver iodide (AgI) was expended, regardless of the method of delivery (i.e., flares near cloud top and/or flares and/or burners at cloud base). The remaining non-seeded units are eligible to serve as controls for seeded units, provided they occurred on a day with actual seeding, through a complicated objective match process, as long as the prospective control was always at least 25 km from the perimeter of a defined seed unit. Matching is done using the actual first-seed time as the reference.

According to WR, in order to be considered a match, the control unit at the time of seeding must satisfy the following criteria:

- Its rain-volume rate (RVR) is within 25% of the RVR of the seed unit,
- Its maximum reflectivity is within 5 dBZ of the maximum reflectivity within the seeded unit, and
- The correlation between prospective control and seed unit RVRs in the 75 minutes prior to first seeding must be \( \geq 0.60 \).
An individual non-seed unit can serve as a control for more than one seeded unit as long as it satisfies the match criteria. Matching of seed and control units can be done for any time period, ranging from the day on which the seed unit was defined to an entire season or seasons. When matching within the day, the match of the weather experienced by both the seed and control units is very good, but as many as half of the seed units cannot be matched due to a lack of suitable controls. When matching within the season or seasons, all seed units can be matched with controls many times (100 matches per seed unit is not unusual), but the weather of each control match may not be well-matched with the weather experienced by the seed unit. This problem can be mitigated to some extent by partitioning the data by the Index of Coalescence Activity (ICA, Strautins et al. 1999, Czys et al. 1996, Czys and Scott 1993), which was calibrated by the AVHRR satellite inferences of cloud microstructure, using the method of Rosenfeld and Lensky (1998), and then matching within each ICA partition.

Although this match process is objective and comprehensive, even perfect matches do not guarantee that inadvertent selection bias, favoring the seed units, has been eliminated from the analyses. It is possible that a knowledgeable seeding pilot might recognize cloud characteristics (e.g., exceptionally hard towers, strong cloud organization, etc.) immediately prior to first seeding that are not readily quantified by the existing match criteria. In such instances, bias favoring the seed units is a possibility.

The apparent advantages of this new method of analysis are that it is computer-automated, permitting the analysis of virtually all of the seeding events in each project, ranging from isolated clouds to massive thunderstorm clusters and lines, and it is objective and comprehensive, eliminating potential human bias during the analysis phase. In addition, the size of the analysis unit (presently 1,964 km²) can be changed as can the match criteria and the analysis can be redone with the new parameters, and it makes the analysis of all projects possible, and facilitates comparisons among projects. Finally, it makes possible the inference of seeding effects as a function of cloud structure, unit age and rain activity at the time of initial seeding, and the method whereby the nucleant was delivered to the clouds.

6.2 Results of Preliminary Analyses

The correlations of the RVR of the seed units with the average RVR for the matched control units are extremely high. The linear correlation coefficients for the seasonal matches for both the High Plains and Edwards Aquifer programs are ≥ 0.99. All seeded units were matched for this time frame. When matching within ±12 hours of the initiation of the seed units, however, only about 60% of the seed units could be matched. In order for more units to be matched in this time frame, the match criteria would have to be relaxed. This is not viewed as a good idea by WR. Conversely, if the match criteria are made even more stringent, even fewer seed units would be matched in the ±12 hour time frame.

Although the matches which make use of seasonal data probably provide a more realistic assessment of seeding effect, WR believe that they too may be somewhat biased, in this case negatively, against inference of an effect of seeding. This may be the case, because most of the control units for use as matches come on the wettest days with strongly forced convective echo activity. Thus, there may be a disproportionate number of “wet” no-seed units available to serve as matches.

The most realistic assessment of seeding effect is provided by sample-weighting the results of matches within the ICA partitions. The apparent effect of seeding for the 1999 and 2000 seasons by 10 hours after initial seeding was +24% in the EAPEP. The increased rain volume per analysis unit was 626 acre-feet. Conservative calculations of benefit to cost ratios for the EAPEP is 9:1. This calculation by WR is based on 197 seeded units, an assumption that 75% of the enhanced rainfall reaches the ground, the value of an acre-foot of water in the Edwards Aquifer region is $100, and total project costs of $1,011,400. These benefit-to-cost ratios likely will change with time depending on the suitability of the clouds for seeding, the aggressiveness of the project meteorologist, and the expertise of the cloud seeding pilots. In addition, selection bias as discussed earlier is a possibility, requiring further investigation. Comparable analyses are now possible for all of the Texas seeding projects.

WR also note that the temporal response to seeding is also of considerable interest. Their plots of seeded and control rainfalls as a function of time (not shown) indicate that the greatest response came about an hour after the initial seeding in the unit. Although the response diminished with time, it seemed to persist in many cases for up to 8 hours. If the units are moving, this means that the effect of seeding is not limited to the boundaries of the target but rather extends outside the target downwind. Thus, those living outside a seeding target in a region that is
normally downwind of the seeding activity are benefiting from the enhanced rainfall without having to pay for it.

7. ACKNOWLEDGEMENTS

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8. REFERENCES


