5A.10 Weather Modification

5A.10.1 Weather Modification and Methods

Weather modification as it has been applied in Texas over the past 25 years involves cloud seeding to either create rain when none would have occurred or to increase rain above what would have naturally occurred. The result of cloud seeding is referred to as rainfall enhancement. The concept of how this occurs is described below.

In natural rainfall, droplets are created from the presence of ice particles (crystals) in the cloud. These crystals are formed when freezing water contacts particles of dust, salt, or sand. The ice crystals form a nucleus around which water droplets attach to make the size of the droplet increase. When the size of a droplet increases sufficiently, it becomes a raindrop and falls from the cloud. Cloud seeding is thought to increase the number of these “nuclei” available to take advantage of the moisture in the cloud to form raindrops that would not have otherwise formed. To be effective, seeding must be done at the correct time and in the correct manner.

As a cloud grows taller, the air temperature in the cloud cools and falls below the freezing point of water. This cooling effect means that the cloud droplets, which are much too small to fall as rain, are also cooled to a point where they respond to crystallization when contacted by an ice particle. Consequently, when there are fewer crystals to act as nuclei for raindrops, there will be less rain than there would have been if more crystals were present. Although crude experiments to enhance rainfall were attempted in the U.S. as early as the mid-1800s, modern weather modification was begun in 1946 through an unintended laboratory event.

In 1946, V. Schaefer was involved with the General Electric Laboratory doing research to create artificial clouds in a chilled chamber. During one experiment, Schaefer believed the chamber was too warm, and, to cool it, he placed dry ice in the chamber. With the chilled water vapor in the chamber, ice crystals formed a cloud around the dry ice. Believing dry ice would not be practical to transport to emerging rain clouds, Schaefer’s colleague, Bernard Vonnegut, searched for a chemical that almost exactly matched the chemical structure of ice crystals. It was found that silver iodide (AgI) was such a chemical.[1] Silver iodide is termed “glaciogenic” because its chemical structure is like ice crystals. The other seeding chemical used when the cloud temperature is too warm for forming ice is calcium chloride (CaCl). Calcium chloride is “hygroscopic,” which means it attracts water.

[1] Jensen, Ric., "Does Weather Modification Really Work?," Texas Water Resources, Summer 1994.

When AgI is introduced into a cloud, the number of ice crystals increases, and the crystals contact water vapor causing it to freeze to the crystal. Considerable heat is released to the atmosphere during the freezing and crystal formation phase. The released heat causes the cloud to grow taller and its vertical wind velocity (updraft) to increase. This results in the cloud being able to pull in more moist air and, thus, create more raindrops. However, not all clouds are potential rainmakers. Generally, cloud seeding is performed with a meteorologist working in tandem with the pilot of the cloud seeding aircraft so that, with direction from the meteorologist, the pilot can target the most promising cloud(s).[2] The criteria used in Texas to find promising clouds, is to locate "feeder" cells near developing cloud formations which have temperatures below 23^{o} F. The target cloud must also have sufficient moisture and airflow to be a candidate. About 20 or 30 minutes prior to the desired rainfall event, the candidate cloud is seeded when the airplane releases AgI particles in a plume, typically at the base of the cloud so the updraft can draw the particles upward and make more contact with water in the cloud. Seeding has another effect on large, potentially dangerous thunderstorms capable of causing hail. Seeding tends to mitigate the extreme freezing that results in forming large particles of ice (hail) and makes the moisture more likely to fall as rain.

The criteria for cloud seeding based on experience in Texas since the early 1970s are the following:

- The cloud must be "convective," meaning that it displays instability in the atmosphere.
- Temperature at the top of the cloud must be 23^{o} F or less.
- The base of the cloud must be less than 12,000 feet elevation.

Clouds having the characteristics listed above exhibit a warm base, a strong updraft, and sufficient heat to carry water vapor to the cloud top.

A summary of recent cloud seeding experiments in Texas, Florida, Cuba, and Southeast Asia has been presented by the Texas Natural Resource Conservation Commission (TNRCC) in a public information document.[3] The TNRCC concludes the following:

- Cloud seeding with AgI increases rain generated by these clouds by extending the life of the clouds, by allowing the clouds to enlarge laterally so that they cover more area, and by slightly increasing the height of the clouds.

[2] Clouds may also be seeded using ground-based silver iodide dispensers. However, in this discussion, only the aircraft method is considered.

[3] Bomar, George, "Some Facts about Cloud Seeding from Recent Research on Rain Enhancement in Texas," Texas Natural Resource Conservation Commission (TNRCC), 1999.

- Rain production of seeded clouds is more efficient than for non-seeded clouds.
- The timing of seeding and the selection of clouds are fundamental. These are such critical factors that "…seeding at the wrong time and in the wrong place(s) may actually decrease the rainfall."[4]

5A.10.2 Potential Rainfall Quantities from Weather Modification

The findings from several Texas cloud seeding programs are summarized below. This will provide a basis for determining the reasonableness of assumptions for the potential quantities resulting from weather modification in the Brazos G Region. The programs to be discussed are the High Plains Underground Water Conservation District (HPUWCD), Southwest Cooperative Program (SWCP), the Texas Experiment in Augmenting Rainfall through Cloud-Seeding (TEXARC), the Colorado River Municipal Water District (CRMWD) Program, the Edwards Aquifer Authority (EAA) Program, and the Southwest Texas Rain-Enhancement Association (SWTREA) Program. Each of these programs is described below:

5A.10.2.1 High Plains Underground Water Conservation District (HPUWCD)

The cloud seeding program run by High Plains Underground Water Conservation District (HPUWCD) covers 12,438 square miles at a total cost of $850,000 per year, or 6.5 cents per acre per year. Long-term precipitation data from this program suggests that as much as 2 inches of additional annual precipitation above the long-term average precipitation has occurred in the region. A map illustrating the long-term average annual precipitation (1945 through 1997) for all the National Weather Service stations in the High Plains Underground Water Conservation District service area was secured, plotted, and contoured on a map of the Water District service area. The contoured map was planimetered, and the total volume of water represented by the average annual precipitation on the 6,869,910-acre area was calculated to be 10,475,488 acft. This indicates an annual average of 18.29 inches of precipitation per acre over the Water District service area for the 1945 through 1997 time period.

In 1999, the total precipitation collected in each of the Water District's 400-plus rain gauge network was plotted on a map, contoured, and planimetered. The total volume of water calculated to have occurred over the Water District service area was 11,599,831 acft for an average of 20.26 inches per surface acre, or 1.97 inches per surface acre above-the long-term average.

[4] Ibid.

In 1998, the total volume of water resulting from precipitation was 81,303,145 acft. This equals 14.50 inches per surface acre, or 3.79 inches per acre below the long-term average. (1998 was the year that smoke from fires in Mexico glaciated the moisture in the clouds. The ice particles were so small that they would not fall as a result of the forces of gravity nor could they be pulled together by seeding to cause them to fall as raindrops. The smoke began to clear in mid-August and it began to rain again.)

In 1997, the first year of the precipitation program, the total volume of water resulting from precipitation in the Water District service area was 11,313,527 acft. This equaled 19.76 inches per surface acre average, or 1.47 inches above the long-term average.

5A.10.2.2 Southwest Cooperative Program (SWCP)

The SWCP was begun in 1986 as a cooperative effort between Oklahoma and Texas "…to develop a scientifically sound, environmentally sensitive, and socially acceptable, applied weather modification technology for increasing water supplies…in the southern High Plains."[5] The area involved was 5,000 square miles located between Midland-Odessa and Lubbock. Random cloud seeding experiments were conducted in 1986, 1987, 1989, 1990, and 1994.

During the period 1987 through 1990, 183 experiments were made (93 seeded, 90 non-seeded). The criteria for selection were the following:

- Liquid water content had to be at least 0.5 gm/m^3 and updrafts had to be at least 1,000 ft/min.
- The target had to be a multiple-cell convective unit.
- No cloud or cell high could exceed 10 km (above ground level).
- Some of the tops had to have temperatures -10^{o} C or colder.

The results confirmed increased rainfall. Compared to the non-seeded cells, the seeded cells displayed an increase in maximum height of 7 percent, an increase in the coverage of the rainfall event of 43 percent, an increase in the storm duration of 36 percent, and an increase in rain volumes of 130 percent.[6]

[5] Bomar, George, William L. Woodley, and Dale L. Bates, "The Texas Weather Modification Program: Objectives, Approach, and Progress," Journal of Weather Modification, Vol. 31, April 1999.
[6] Rosenfeld, D. and W.L. Woodley, "Effects of Cloud Seeding in West Texas: Additional Results and New Insights," Journal of Applied Meteorology, Vol. 32, 1848-1866, 1993.

5A.10.2.3 Texas Experiment in Augmenting Rainfall through Cloud Seeding (TEXARC)

The State of Texas implemented the TEXARC Program in 1994 and 1995 to investigate physical processes within large storms in the San Angelo area. This research was focused on understanding the best ways of seeding clouds to make them more efficient producers of water, rather than on quantifying results. The results showed that seeding must be within the super-cooled updraft region of the cloud in order to increase rainfall. From this research it was shown that the seeding agent must be carefully placed either directly in the top of the updraft, or at the entrance to the updraft at the base of the cloud.

5A.10.2.4 Colorado River Municipal Water District (CRMWD) Program

Started in 1971, the CRMWD Program is the longest-running operational weather modification program in Texas. The target area is roughly the upper Colorado River basin upstream from Spence Reservoir, comprising some 3,600 square miles. The goals for the program have always been: first, to increase water supplies to Lake Thomas and Spence Reservoir, and secondly, to increase rainfall to agricultural areas. The reported long-term results are that there was a 34 percent increase (above normal historic precipitation) in the seeded areas and a 13 percent increase in non-seeded areas.[7,8]

5A.10.2.5 Edwards Aquifer Authority (EAA) Program

Note: Substantial portions of this program description were reproduced from the EAA web page, e-aquifer.com, and are presented here unedited.

The Edwards Aquifer Authority board of directors voted in the Fall of 1997 to obtain a permit to conduct precipitation enhancement, or cloud seeding, from the TNRCC. The Authority contracted with Weather Modification, Inc., to complete and submit the permit application on the Authority's behalf, and to work with the TNRCC. The permit was granted by TNRCC in October 1998 and is valid for four years from January 1999 through December 2002. The permit allows the Authority to conduct precipitation enhancement anytime during the year, including the traditional period of April through September. The Authority has committed $500,000 for the 1999 program with half the expenses reimbursed by the TNRCC.

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[7] Jones, R. "A Summary of the 1988 Rainfall Enhancement Program and a Review of the Area Rainfall and Primary Crop Yield," Report 88-1 of the Colorado River Municipal Water District, 75 pages, 1988.

[8] Jones, R. "A Summary of the 1997 Rainfall Enhancement Program and a Review of the Area Rainfall and Primary Crop Yield," Report 97-1 of the Colorado River Municipal Water District, 54 pages, 1997.

The target area of the program covers over 6 million acres at a cost of about 4 cents per acre (Table 5A.10-1).

Table 5A.10-1.
Edwards Aquifer Authority Weather Modification Program Counties

Target Counties	*Operational Counties*	*SCTWAC Counties**
Bandera, Bexar, Blanco, Caldwell, Comal, Guadalupe, Hays, Kendall, Kerr, Medina, Real (east of U.S. Highway 83), and Uvalde	Gillespie, portions of Atascosa, Burnet, Frio, Kimble, Llano, Real, Wilson, and Zavala	Calhoun, DeWitt, Goliad, Gonzales, Karnes, Nueces, Refugio, San Patricio, Victoria, Atascosa, Wilson, Uvalde, Medina, Bexar, Comal, Hays, Guadalupe and Caldwell

* South Central Texas Water Advisory Committee (SCTWAC), as created by SB 1477.

Each county in the target and in South Central Texas Water Advisory Committee (SCTWAC) areas of the program can appoint a representative to sit on a Precipitation Enhancement Advisory Group. The group will work with the Authority in alerting the contractor about local conditions. The ways this committee has worked include communicating saturation conditions so that flights are suspended to avoid flood conditions and suspending flights during harvesting of crops.

The first year of this program operated from April 15 to September 15, 1999. The assumption for enhanced aquifer recharge was 10 percent above the recharge quantity, which would occur without enhancement.

5A.10.2.6 Rainfall Enhancement Programs Underway in Summer 1999

Several active cloud seeding programs were performed during the summer of 1999 including some as part of the programs described above. The programs, the counties they cover, and the approximate areas of coverage are presented in the Table 5A.10-2.

Although rainfall enhancement through cloud seeding has been practiced and studied in Texas and other states for many years, the benefits of rainfall enhancement for increasing water yield are not well determined. There is documentation regarding other benefits of cloud seeding, particularly with regard to impacts on agricultural production. The following section provides descriptions of quantified benefits resulting from cloud seeding in Texas and an estimate of the benefits to the region.

Table 5A.10-2.
Cloud Seeding Programs Underway in Texas during Summer 1999

Cloud Seeding Program	Counties Involved	Area (sq. miles)
Colorado River MWD	Bordon, Mitchell, and parts of Dawson, Howard, Sterling, Nolan, and Scurry	3,500
West Texas Weather Modification Association	Glasscock, Reagan, Crockett, Sutton, Schleicher, Irion and part of Tom Green	9,688
South Texas Weather Modification Association	Frio, Atascosa, McMullen, Live Oak, Bee, Karnes, Wilson	6,891
High Plains Underground Water Conservation District	Yoakum, Terry, Lynn, Cochran, Hockley, Lubbock, Bailey, Lamb, Hale, Parmer, Castro, Floyd, and part of Deaf Smith, Potter, Randall, and Crosby	12,438
Texas Border Weather Modification Association	Val Verde, Kinney, and Maverick	5,922
Edwards Aquifer Authority Program	Medina, Bandera, Kerr, Kendall, Blanco, Hays, Caldwell, Comal, Guadalupe, Bexar, and part of Real	8,500
Southwest Rain Enhancement Association	Uvalde, Zavala, Dimmit, La Salle, and Webb	9,141

5A.10.3 Potential Quantities of Water Supply Resulting from Weather Modification in the Brazos G Region

The benefits resulting from cloud seeding in the Brazos G Region may include improvements in environmental and economic conditions. Environmental conditions in streams and reservoirs can be improved by increased freshwater flows and the improvements can be measured using water quality parameters. Economic conditions can be improved by increasing crop production, by increasing animal production as a result of increasing the food supply, and by increasing ground and surface water supplies. Increasing water supplies can further improve economic conditions by affecting recreation, agriculture, municipal, and industrial activities in beneficial ways.

Performance data from cloud seeding programs typically focus on the rainfall event and parameters such as storm duration, cloud height, storm coverage (cloud area), and rainfall amount, rather than on water supply parameters like increased stream flows and increased reservoir storage. Where water supply parameters have been measured in cloud seeding programs, the results appear to be positive. For example, Colorado River Municipal Water District (CRMWD) reservoir storage increased from 14,000 acft to 200,000 acft in Lake Spence and from 26,000 acft to 30,000 acft in Lake Thomas since the inception of cloud seeding in the Big Spring and Snyder areas.[9] Also, the Twin Buttes and Fisher Reservoirs increased from a combined 40,000 acft to a combined 230,000 acft during a cloud seeding program sponsored by the City of San Angelo between 1985 and 1989.[10]

To determine how much additional water can be developed from weather modification in the Brazos G Region requires a sequence of information. This information sequence includes: (1) the quantity of additional rainfall developed through cloud seeding; (2) the quantity of additional runoff; and (3) the quantity of additional runoff that was ultimately transported to a reservoir or was recharged to an aquifer. In the 1994 Edwards Aquifer Recharge Enhancement Project, Phase IV A, normal and enhanced recharge rates were computed for target recharge sites. The enhanced rates were developed to simulate the additional quantities of recharge that would naturally enter the aquifer without the benefit of man-made recharge structures. This 1994 Edwards Aquifer recharge study provides a baseline case from which to compute an example of potential water supply development from weather modification, as is explained below.

One way to estimate the potential for enhancing recharge through weather modification would be to increase the precipitation at an assumed rate and recompute enhanced recharge. The EAA program described above covers the same region as the areas modeled in the 1994 study. Therefore, an estimate has been made using the Sabinal River watershed (241 square miles) model with an assumed increase in rainfall over the same years studied previously in order to determine whether estimates for recharge would show increases if rainfall increased. This modeling and resulting computations show an annual average increase in estimated recharge of 9 percent, assuming a 15 percent increase in rainfall during the warm months (April through September) for the years 1990 through 1996 (Table 5A.10-3). The model shows an annual average estimated increase of 3,173 acft (0.02 acft/acre) of recharge from the Sabinal River watershed. Although the EAA cloud seeding program covers the same areas previously modeled, an estimate of total increase in recharge resulting from the program was not developed. Since the increase in rainfall in an area where there is no pre-or post- cloud seeding data can only be assumed, it would be an inequitable comparison with most other options to extrapolate

[9] Jensen, Ric, Op. Cit., 1994.
[10] Jensen, Ric, Op. Cit., 1994.

Table 5A.10-3.
Simulation of Increased Annual Edwards Aquifer Recharge Due to a 15 Percent Increase in Precipitation — Sabinal River Watershed

Year	Baseline Recharge Estimate (acft)	Recharge Estimate with 15 percent Increased Precipitation (acft)	Difference (acft)	Percent Difference
1990	32,526	35,822	3,296	10%
1991	41,319	45,361	4,042	10%
1992	67,724	72,719	4,995	7%
1993	27,761	29,745	1,984	7%
1994	24,219	26,833	2,614	11%
1995	30,855	33,574	2,719	9%
1996	10,537	13,093	2,556	24%
Average	33,563	36,736	3,173	9%

[1] The Sabinal River watershed has an area of 241 square miles, or 154,240 acres.

computer modeling results like those above over the entire region. To be an equitable comparison, the results of cloud seeding in terms of increased rainfall, aquifer recharge, and reservoir storage would have to be predictable, verifiable, and comparable to unit firm yields developed from other options. Since these criteria cannot be met at this time, no such estimates can be made.

The methodology for estimating enhanced recharge as described above for the Edwards Aquifer area is not applicable for most of the aquifers in the Brazos G Region because the nature of recharge is different. The Edwards, a karst aquifer in south-central Texas extending into Bell County, has direct surface conduits and recharges rapidly, whereas most other aquifers in the region require more time to recharge. Thus, attempting to quantify the impact of cloud seeding in the Brazos G Region on water supplies should be focused on the improvement in soil moisture content as a means of lessening the need for pumped irrigation of crops. If less groundwater is needed for crops because enhanced precipitation improves soil moisture content, then there is an overall enhancement to groundwater supplies.

5A.10.4 Environmental Effects of Weather Modification

Although cloud seeding is not a new technique, its effectiveness has been difficult to measure. Since Texas has established a permit procedure, administered by TNRCC, data are being collected for a more scientific study of cloud seeding effectiveness and management. Originally conceived as a means to end droughts, cloud seeding may work best during periods of normal rainfall. Weather modification is now considered a long-term water augmentation strategy for freshwater supplies.[11]

The amount of silver iodide and calcium chloride used during a seeding event is negligible and too dispersed to have a measurable effect on the environment. Safe handling and storage of these materials prior to dispersal are a larger concern. Both are normally used in industrial applications and printing. Therefore, procedures for handling and storing silver iodide are well documented. There are no known environmental problems associated with this option.

5A.10.5 Estimated Costs of Weather Modification

Examples of current costs for weather modification are available from two of the programs described in previous sections. The cloud seeding program run by HPUWCD covers 12,438 square miles at a total cost of $850,000 per year (6.5 cents per acre/year). The program sponsored by the Edwards Aquifer Authority covers 8,500 square miles and costs $500,000 (9.1 cents per acre/year).

5A.10.6 Implementation Issues

This water supply option has been compared to the plan development criteria, as shown in Table 5A.10-4.

In terms of a measurable and dependable regional water supply option, weather modification in the form of cloud seeding appears to be a beneficial, but uncertain, source of usable water. However, data are not adequate to specify firm yield. Using the following assumptions regarding factors that influence aquifer yield, it may be possible to gain a sense of the potential increase in soil moisture or additional runoff that might result from cloud seeding:

1. Assume an increase in rainfall during warm months resulting directly from cloud seeding.

[11] Bomar, George, TNRCC Senior Meteorologist, Austin, Texas.

Table 5A.10-4.
Comparison of Weather Modification Option to Plan Development Criteria

Impact Category	*Comment(s)*
A. Water Supply:	
1. Quantity	1. Uncertain
2. Reliability	2. Low
3. Cost	3. Reasonable
B. Environmental factors	
1. Environmental Water Needs	1. None or low impact
2. Habitat	2. No impact
3. Cultural Resources	3. No impact
4. Bays and Estuaries	4. No impact
C. Impact on Other State Water Resources	• No apparent negative impacts on state water resources; potential benefit to Edwards, Trinity, and Carrizo Aquifers, due to increased water for recharge; potential benefit to farmers and ranchers through increased rainfall; no effect on navigation
D. Threats to Agriculture and Natural Resources	• Potential threat, due to slightly increased chance of flooding
E. Equitable Comparison of Strategies Deemed Feasible	• Option is considered to meet municipal and industrial shortages
F. Requirements for Interbasin Transfers	• Not applicable
G. Third Party Social and Economic Impacts from Voluntary Redistribution	• Not applicable

2. Assume that the increased rainfall is managed in order to prevent flooding but falls at a time when antecedent soil moisture is high enough to create runoff.

One important potential benefit of cloud seeding is that a part of the agricultural water supply needs (irrigated and dryland crops and rangelands) could be met. For example, higher rainfall would lower the quantities of irrigation water that has to be withdrawn from the aquifers of the Brazos G Region, and dryland production would benefit from increased rainfall. This could be a significant water supply option for agricultural uses. Over a sufficient period, agricultural production data could be gathered to ascertain whether that crop yield, animal production, and other measurable agricultural parameters have increased. These data could be compared to corresponding data gathered prior to the cloud seeding program. For a relatively minor cost, cloud seeding could perhaps meet some of the agricultural needs, as well as make contributions to aquifer recharge and streamflows of the region that could be developed to meet municipal and industrial needs.