Alternative: Increase Precipitation, Runoff, and Infiltration Through Cloud Seeding

Acknowledgements: This white paper was produced by Daniel B. Stephens & Associates, Inc., with assistance from the Jemez y Sangre Water Planning Council and with input from a water planning charrette held in February 2002. Contributing authors include Don A. Griffith, North American Weather Consultants (primary author), Susan C. Kery (legal), and Ernest Atencio (socioeconomic).

1. Summary of the Alternative

Cloud seeding, sometimes referred to as weather modification, is a technology that has developed since some historic discoveries in the late 1940s. These discoveries demonstrated, first in the laboratory and later in the atmosphere, that clouds containing super-cooled water droplets (droplets colder than freezing) could be altered through seeding to produce tiny ice crystals that could grow into snowflakes. These discoveries opened the door to the possibility of modifying certain types of naturally occurring clouds to produce more precipitation. Such a possibility is important, not only because many types of clouds contain super-cooled water droplets, but because the presence of such droplets often means that these clouds will be inefficient in producing precipitation. Seeding that targets super-cooled water droplets is commonly known as glaciogenic seeding.

The initial optimism that followed these discoveries led to a flurry of both research and operational programs in the 1950s. Some skepticism developed when the perceived results of these programs were not as promising as hoped. Nevertheless, a considerable amount of additional research was conducted in this field in the United States and a number of other countries from the 1950s to the 1990s.

At the present time there is still some disagreement in the scientific community about the efficacy of cloud seeding. Professional societies do, however, have policy statements that are guardedly optimistic concerning this technology (i.e., American Meteorological Society, 1998). These statements all agree that the likelihood of success depends on the type of weather modification being considered:

- The most scientifically accepted capability of man to alter clouds is in the realm of cold (32°F or colder) fogs. Dry ice dropped through such clouds or compressed gases released into these fogs will create snowflakes that fall to the ground, resulting in an improvement in visibility. A typical application is at airports that experience disruption in flight landings due to dense fog.

- The next most accepted capability is that of treating winter clouds passing over mountain barriers (called orographic seeding programs). With some of these clouds, seeding can result in precipitation increases of 10 to 15 percent.

- The effectiveness of summer cloud (typically cumulus clouds) modification is less proven than that of winter mountain cloud modification. There is, however, considerable evidence that individual clouds can be seeded to produce additional precipitation. Less evidence exists that seeding summer clouds leads to area-wide increases in precipitation.

- The least scientifically accepted weather modification technique is that of hail mitigation or reduction.

In spite of the mixed scientific reviews, a large number of cloud seeding programs are being conducted in numerous locations and countries. For example, approximately 13 winter cloud seeding programs are typically conducted in California each winter. Texas had 7 large summer programs in 1999 (Bomar et al., 1999) and will have approximately 10 programs in operation next summer. China has a large number of active programs.

Perhaps one of the reasons for the number of operational programs is the willingness of program sponsors to accept some uncertainty given the potentially significant impact that a cloud seeding program may produce. While the scientific community requires a 95 percent confidence level (i.e., no more than a 5 percent likelihood that the observed result could occur by chance) to accept results from research programs, the public sector is apparently willing to accept lower confidence levels (i.e., 80 percent). Less scientifically rigorous evaluations of a number of these operational programs have indicated beneficial effects from precipitation enhancement programs (both winter and summer) and some hail mitigation programs.

An interesting parallel regarding the level of confidence necessary to proceed with a cloud seeding project can be drawn from the field of weather forecasting which, like cloud seeding, inherently has some inaccuracy due to the large number of variables that directly drive the weather. The accuracy in 1- to 3-day weather forecasts is on the order of 85 percent correct and, as would be expected, less for longer-range forecasts. Yet the National Weather Service (NWS) routinely provides weather forecasts for 1 to 3 days and beyond, despite the fact that they are not 95 percent accurate.

2. Technical Feasibility

Cloud seeding projects could be conducted in the Jemez y Sangre region in both winter and summer seasons. A study by Duke Engineering & Services (2001) indicates that a large majority of the surface streamflow in the various sub-basins of the study area is the result of melting snow that accumulates on the Jemez and Sangre de Cristo Mountains during winter. Hence, increasing winter snow pack through cloud seeding could be beneficial to the region. Groundwater recharge is also primarily derived from precipitation that falls on these two mountain barriers. Little groundwater recharge is derived from precipitation that falls over lower-elevation areas.

2.1 Winter Orographic Cloud Seeding

Winter cloud seeding projects have been conducted in the western United States for many years, with some ongoing projects in California dating back to the early 1950s. The primary targets of these projects have been mountainous areas for many reasons, including:

- High amounts of natural precipitation due to the orographic effect (the lifting of moist air over mountain barriers) result in maximization of condensation and precipitation.

- An excess of water (more water available than required to meet evapotranspiration requirements) in these areas results in surface and underground runoff into lower-elevation areas.

- The orographic lift generates very favorable conditions for seeding due to the production of zones of super-cooled water droplets over the upwind slopes of these barriers.

- The orographic lift favors the transport of seeding material released from the ground into these zones of super-cooled liquid water.

A 4-year research-oriented cloud seeding project was conducted from 1969 to 1972 in the Jemez and Sierra Nacimiento Mountains of northern New Mexico (Keyes et al., 1972). This project used ground-based portable silver iodide generators to seed portions of winter storms on a random basis. A statistical analysis of the results indicated an increase during the seeded 24-hour periods of 13 percent. Some of the more interesting trends suggested by the results were that (1) the positive seeding effects seemed to occur in the two 6-hour blocks from 2300 to 1100 Mountain Standard Time (MST) and (2) the highest indicated increases occurred with the 700-millibar (mb) (approximately 10,000 feet above mean sea level [ft msl]) winds blowing from 135 to 180 degrees.

North American Weather Consultants (NAWC) has conducted a large number of operational winter projects since 1950, including a number of projects in the State of Utah beginning in 1974. Evaluations of these projects have consistently indicated increases in target area precipitation (Griffith et al., 1991; Griffith et al., 1997).

The above information and that contained in the Duke study (2001) suggest that a winter cloud seeding project would be feasible during the months of October through April over the Jemez and Sangre de Cristo higher-elevation watersheds that are within the various sub-basins of the study area. All sub-basins should be suitable except the Caja del Rio, which does not contain a significant orographic barrier. A general definition of the proposed target areas would be drainage basins higher than 7,500 ft msl in elevation. Such a project could use either ground-based delivery systems, aircraft, or a combination of the two to dispense silver iodide particles into clouds that form on the upwind sides of these barriers. Clouds in these locations have been shown to frequently contain super-cooled liquid water droplets, which are the targets of glaciogenic seeding.

The NWS provides a number of products that can be used to direct the real-time seeding decisions on such a project. These products include twice daily upper-air rawinsonde observations, surface weather reports, surface- and upper-air analyses, weather satellite photographs, next generation radar (NEXRAD) weather radar displays, and weather forecasts.

Most technical obstacles to conducting a project of this type have been addressed and overcome in the performance of similar projects in the western United States dating back to the 1950s. However, two concerns remain for a cloud seeding program in the study area:

- *The relatively warm temperatures of the winter storms that affect this area.* Silver iodide does not become an effective ice nucleant until it reaches temperatures in the cloud of approximately −4 to −5°C. The results of an NAWC preliminary analysis of the temperature at the height of the 700-mb (approximately 10,000 ft msl) level and atmospheric stability from the surface to 700 mb suggest that ground-based silver iodide generators would be ineffective in approximately 25 percent of the winter storms. Aircraft would be necessary to seed these storms.

- *The relatively narrow nature of the two mountain barriers.* The goal of a winter seeding project is to have the effects occur in the mountainous areas. Yet the silver iodide material needs time to reach the −5°C level and interact with cloud droplets, causing them to freeze, and then the resulting ice crystals need time to grow into snowflakes and fall to the ground. If the winds are strong or the formation of snowflakes takes too long, the effects of seeding will occur some distance downwind, possibly beyond the extent of the mountain barriers. There are a couple of solutions to this problem: (1) fast acting complexes of silver iodide can be used to speed up the formation of ice crystals or (2) aircraft seeding can be used in the stronger wind cases (in which case, the aircraft is flown further upwind to compensate for the stronger winds).

2.2 Summer Convective Cloud Seeding

The study areas receive a considerable amount of their annual precipitation in the summer months due to summer monsoons. A monsoon is the result of clockwise flow around a semi-permanent Bermuda high pressure area that brings moisture into New Mexico from the Gulf of Mexico. This influx of moisture provides the fuel to drive the formation of thunderstorms over the study area, which produce significant amounts of precipitation. The summer activity peaks in the month of August.

Thunderstorms initially begin as cumulus clouds. A large number of research and operational cloud seeding projects designed to increase precipitation from cumulus clouds have been conducted. Results from these projects have indicated that substantial increases from individual cumulus clouds are possible but that the possibility of impacts on area rainfall over a season is less conclusive (Rosenfeld and Woodley, 1993). Less rigorous evaluations of a number of operational projects have, however, indicated increases in season area rainfall from seeded clouds (Jones, 1997).

Selective seeding of growing towering cumulus clouds with silver iodide flares in the study area is considered feasible. This technique consists of an aircraft penetrating the tops of towering cumulus clouds at the –5 to –10°C level. Silver iodide flares are dropped from the aircraft into the updraft regions of these clouds. These updraft regions have been shown to contain large amounts of super-cooled water droplets, which are the targets in glaciogenic seeding.

Streams are fed by snowmelt and the recharge of the snowmelt that issues as springs. Therefore the acequias, City of Santa Fe and riparian ecosystems, and others who benefit from flow in the streams would benefit from the increased snowmelt and resulting groundwater recharge that would result from seeding over the mountains. Seeding would be conducted over other lower-elevation areas as well, with the goal of producing direct rainfall on croplands (either dryland farm or rangelands and irrigated agriculture). Increased rainfall over irrigated agricultural areas would have the impact of lowering demands on surface or underground water supplies.

Some projects use cloud base seeding of cumulus clouds. Recent investigations in South Africa, Mexico, and Texas have used salt (NaCl) flares as a precipitant to seed near the bases of cumulus clouds in the summer months. To date, these programs have indicated a positive effect only for individual clouds, and although promising, this technology will require more research and demonstration to prove it as a viable method of cloud seeding. In addition, this approach has not been recommended due to the underlying mountainous terrain in much of the area, which would preclude the application of this approach.

Weather radars are typically used to direct the cloud seeding operations. The other NWS products mentioned in the Section 2.1 would also be used. As in the case with winter seeding, since this type of project has been conducted previously in a large number of operational projects in the U.S. and a number of other countries, there are few technical obstacles to be overcome.

3. Financial Feasibility

The costs of conducting winter or summer cloud seeding projects can vary according to the intended size of the target area, the length of the seeded period, and the amount of personnel and equipment needed to perform the work. Such costs can be expected to range from $75,000 to $300,000 per season of operations. Analyses of a number of operational cloud seeding projects have indicated that precipitation from cloud seeding projects generally can be produced in the range of $1 to $10 per acre-foot. Depending upon the value of the water in a given area, the benefit/cost ratios of such projects often range from 5/1 to 20/1.

4. Legal Feasibility

Cloud seeding is governed by the Weather Control Act (NMSA 1978, §75-3-1 *et seq.).* As declared in the Act, "the State of New Mexico claims the right to all moisture in the atmosphere which would fall so as to become a part of the natural streams or percolated water of New Mexico, for use in accordance with its laws" (NMSA 1978, §75-3-3). Therefore, pursuant to the

Act, any water gained through cloud seeding would be considered unappropriated water and therefore subject to appropriation through the statutory appropriation process.

Weather control, cloud modification, or attempts to control precipitation are activities that must be licensed. Such licenses are issued by the Weather Control and Cloud Modification Commission, which is a three-member commission appointed by the board of regents of the New Mexico Institute of Mining and Technology (NMSA 1978, §75-3-13). Such a license will only be issued upon the demonstration of (1) sufficient financial responsibility necessary to meet the obligations likely to result from weather control or cloud modification and (2) the skill and experience necessary to accomplish weather control without injury to persons or property (NMSA 1978, §75-3-7). Thus, the only legal restraints placed on the region related to cloud seeding are the licensing requirements set forth in the Weather Control Act.

5. Effectiveness in Either Increasing the Available Supply or Reducing the Projected Demand

Increases in the winter snow pack in targeted watersheds typically ranges from 5 to 15 percent. These increases are spread over rather large higher-elevation areas, where a large majority of the increases translate into additional surface streamflow. Several studies have indicated that the percentage change in runoff resulting from an increase in precipitation can be higher than the percentage change in precipitation (Stauffer and Williams, 2000). To demonstrate the potential magnitude of an increase in snow water content, 10 percent of the average water content at the Natural Resources Conservation Service (NRCS) Snotel site in the Sangre de Cristo Mountains would amount to 1.45 inches. Given that a total of 83,000 acres in the region are above 9,000 feet, an elevation where most of the snowfall occurs, the total amount of additional snow pack produced through winter cloud seeding could be about 10,000 acre-feet (1.45 inches [0.12 foot] x 83,000 acres). Based on the results of recent studies at a site in Arizona at an elevation of 9,200 feet (Godfried et al., 1997), in which about 61 percent of snowpack was observed as streamflow, the additional 10,000 acre-feet of snow pack might produce about 6,000 acre-feet of streamflow. Similarly, if a 5 percent increase in snowpack results from a cloud seeding program, about 3,000 acre-feet of streamflow would be gained.

Increases in rainfall from a summer project over irrigated lands would lower the demand on stored, diverted, or underground water supplies. Increases in summer rainfall over the mountainous areas may produce additional groundwater recharge in lower-elevation areas, but no additional surface runoff is expected from a summer cloud seeding program. Area increases in summer precipitation should also be in the 5 to 15 percent range. A 10 percent increase in May through September rainfall at the Santa Fe 2 observing station would amount to 0.85 inch of rainfall, while a 10 percent increase at the Santa Fe NRCS high-elevation Snotel site would amount to 1.94 inches of additional rainfall.

6. Environmental Implications

A considerable amount of research has been conducted on the potential environmental impacts of cloud seeding projects. Much of this research in the western United States has been funded by the Bureau of Reclamation under their Project Skywater project. Some of the more common concerns that were addressed included toxicity of seeding materials (i.e., silver iodide), extension of the snowmelt in higher elevations, and increases in soil erosion. Published results from these projects indicate no significant impact from winter or summer projects (e.g., Smith and Berg, 1979), and no significant environmental impacts are expected from any winter or summer cloud seeding projects conducted in the study area. However, because EPA has issued a Human Health Advisory level of 180 μg/L for silver in water (New Mexico Environment Department Water Quality Control Commission standard is 50 μg/L) and 3,900 mg/kg in soil, a careful study must be conducted to ensure that these standards would not be exceeded, particularly considering the potential for bioaccumulation.

7. Socioeconomic Impacts

The Jemez y Sangre region of northern New Mexico is distinguished by its rural and agricultural character, predominantly Indian and Hispano population, localized land-based economies, and pockets of persistent poverty. In particular, its Indian and Hispano populations represent some of the most unique cultures in the world, products of a long history of continuous human habitation, adaptation, and cultural blending. Land-based Indian and Hispano cultures still thrive, carrying on centuries-old cultural traditions that include distinctive land-use and settlement patterns, agricultural and irrigation practices, natural resource stewardship practices, social relations, religious activities, and architecture. An example is the ancient *acequia* tradition, which is vital both as a sustainable irrigation system for subsistence and market agriculture and as part of the social glue that holds together rural communities.

The survival of these deeply rooted local traditions is essential for the continuity of rural culture and communities and, in turn, for the local tourism industry, which is built in large part upon the singular cultural and historical personality of the region. Preservation of these traditions is therefore an important consideration in determining the socioeconomic and cultural impacts of regional water planning.

Increasing precipitation, runoff, and infiltration through cloud seeding would increase surface water and groundwater yield for beneficial uses, including acequias and other traditional uses, thus directly benefiting associated socioeconomic and cultural values. Direct economic impacts from the conduct of cloud seeding projects include additional streamflow available for irrigation or municipal uses, recharge of underground aquifers, which can also be used for irrigation and municipal water supplies, direct rainfall on croplands and rangelands, which can increase production, and reduction of irrigation demands due to direct rainfall on croplands. Secondary impacts include favorable impacts to farming and ranching communities' economies if crop or livestock production rises and lower fire danger due to increased rainfall over forested areas during the summer. Beyond measurable economic impacts, increasing surface water and groundwater yield for rural uses, including acequias and domestic wells, directly benefits the many socioeconomic and cultural values associated with traditional communities.

Two specific concerns are sometimes mentioned regarding cloud seeding projects:

- *The possibility of increasing snow removal costs from mountain roads in winter project areas.* Studies conducted in Colorado and California have indicated little impact in this regard.

- *A reduction in precipitation in downwind areas due to upwind seeding.* Based upon the analysis of a number of research and operational projects, precipitation appears to be increased rather than decreased in these downwind areas. The reasons for this outcome are several, but the primary reason is that in any given year large amounts of water suspended in vapor form pass over the U.S., of which only approximately 10 percent reaches the ground as precipitation. Advisory groups can be formed to provide a forum for the public to become informed about the project(s) and also can be used to provide input to the conduct of the cloud seeding project (i.e., excessive rainfall on croplands may necessitate a temporary suspension of cloud seeding activities).

In addition, the perception of cloud seeding as “meddling” with natural climatic processes would possibly generate some negative public opinion and opposition. Negative perceptions of cloud seeding could be minimized if it were conclusively shown through targeted public education that it would be environmentally/climatically benign and would not have an adverse effect on downwind precipitation. Depending on the expense and financing of a cloud seeding program, increasing available water with this alternative would probably reduce the cost for all water users.

8. Actions Needed to Implement/Ease of Implementation

Cloud seeding projects are relatively easy to start or to stop. Some New Mexico licensing requirements must be met to begin a project. There are also some Federal initial, interim and final reporting requirements. Contracts are typically awarded to firms that conduct cloud seeding projects, thus entailing the preparation of project specifications and solicitation and evaluation of proposals. In general, 1 to 2 months are required to set up a project following contract award and 1 to 2 weeks to dismantle a project. This fast response aspect of cloud seeding is often viewed as an asset in contrast to other water augmentation alternatives that may take much longer to implement. The American Society of Civil Engineers has published a manual on cloud seeding that provides useful information on the steps needed to implement a project as well as other useful information concerning this subject (ASCE, 1995).

For a cloud seeding project to move forward, the formation of partnerships is recommended. Interested parties may want to recruit local entities to conduct a pilot program and propose cost-sharing with the Interstate Stream Commission (ISC). A public information program will be necessary to garner public support and facilitate the solicitation of potential sponsoring agencies.

Review of recent experiments by ISC in the Pecos Valley and research of silver iodide monitoring in California and Utah are recommended next steps before proceeding with a project. For a large-scale cloud seeding program, modeling of the predicted runoff would be necessary to establish the program's viability and garner support and funding.

9. Summary of Advantages and Disadvantages

Potential advantages of implementing cloud seeding projects over the study area are:

- Potential 5 to 15 percent increases in precipitation
- Potential 5/1 to 20/1 benefit/cost ratios
- Potential increases in surface runoff and underground water recharge
- Secondary beneficiaries (those parties that will indirectly benefit from increases in precipitation)
- No significant environmental impacts
- Relative ease in implementing projects quickly with no long term obligations
- Possibility of incorporating the design of a large number of operational projects that have been conducted in a number of countries with apparent success

Potential disadvantages of implementing cloud seeding programs over the study area are:

- Difficulty in evaluating the actual impacts of seeding on precipitation
- Scientific disagreement about the effectiveness of cloud seeding
- Need to make long-term commitments to conduct projects rather than viewing cloud seeding as only a drought relief tool
- Significant cost, which may require funding from several entities (i.e., local irrigation groups, municipalities, farm groups, state agencies) working together
- Ability to divert water generated from cloud seeding

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