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30+ WINTER SEASONS OF OPERATIONAL CLOUD SEEDING IN UTAH

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ABSTRACT

North American Weather Consultants (NAWC) has conducted operational winter cloud seeding programs in many of the mountainous areas of Utah since 1974. The goal of all of these programs has been to enhance winter snowpack accumulation in several mountainous target areas throughout the State. Studies have demonstrated that a large majority of the annual runoff in Utah streams and rivers is derived from melting snowpacks, thus the focus on wintertime seeding. Augmented water supplies are typically used for irrigated agriculture or municipal water supplies. Programs are typically funded at the county level with cost sharing grants from the Utah Division of Water Resources.

Cloud seeding is accomplished using networks of ground-based, manually operated silver iodide generators located in valley or foothill locations upwind of the intended target mountain barriers. As such, these programs are classified as orographic winter cloud seeding programs. Orographic winter cloud seeding programs are typically categorized as those with the highest level of scientific support based upon capability statements of such organizations as the American Meteorological Society, the World Meteorological Organization, and the Weather Modification Association.

NAWC historical target/control evaluations of these Utah programs based upon high elevation precipitation and snow water content observations indicate apparent increases in target area average precipitation or April 1st snow water content of approximately 5-20%.

The Utah Division of Water Resources conducted an independent assessment of the seeding programs in 2000. That assessment confirmed the NAWC indicated increases in snow water content, and then took the additional step of estimating the increases in annual streamflow resulting from the estimated increases in snow water content. Average annual increases from four seeded areas were estimated to total 249,600 acre feet. Factoring in the cost of conducting these programs resulted in an estimate of the average cost of the augmented runoff to be $1.02 per acre-foot.

1. BACKGROUND

An early winter cloud seeding program was conducted in southern Utah during the period of 1951 through 1955. The University of Utah Meteorology Department (Hales, et al, 1955) and the American Institute of Aerological Research (1955) made evaluations of the effects of this seeding program. The two evaluations resulted in conflicting results, and the program ended.

North American Weather Consultants was contracted by a group of central and southern Utah Counties to initiate a winter cloud seeding in the mountainous areas of central and southern Utah. This program began in the 1973-74 winter season and continued in the 1974-75 winter season. The initial impetus to initiate this program was due to drought conditions that impacted southern Utah during the 1972-73 winter season. The participating counties provided funding for these programs. The Utah legislature passed a comprehensive weather modification law in 1973 (73-15-3 through 8) (Stauffer, 2001). This legislation authorized the Utah Division of Water Resources to both regulate and develop cloud seeding programs within the State. The Division of Water Resources began cost sharing with the local supporters of this central/southern cloud seeding program during the 1975-76 winter season. This program has continued to the present except for a break from 1983-1987, which was an extremely wet period throughout the State of Utah. Figure 1 provides a map of Utah Counties for reference purposes.

A dry winter, 1987-88, led to an expansion of the seeding activities into northern Utah beginning with the 1988-89 winter season. One program area, encompassing the mountainous areas of two northern Utah Counties (Box Elder and Cache) has been operational most winters from the 1988-89 winter season to the present. Another operational area encompassed the mountainous areas that ring the east side of Salt Lake County. This program operated during the 1987-88 through the 1994-95 winter

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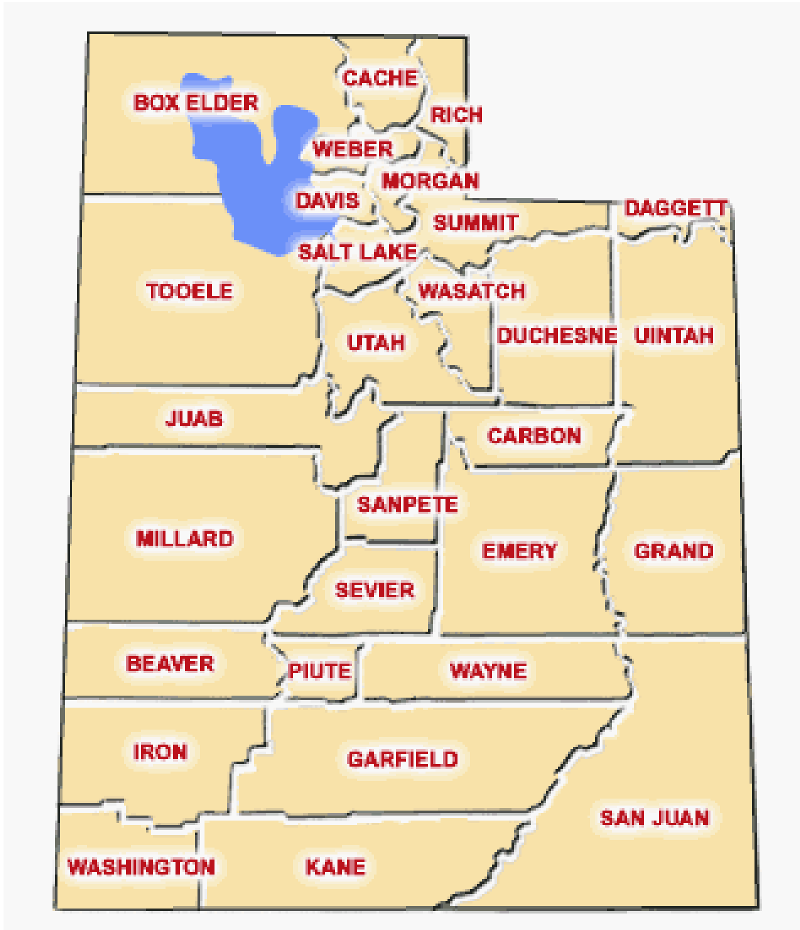

Figure 1 Utah Counties

seasons. Another program was developed to target the Western Uinta Mountains located in northeast Utah. This program began in the 1988-89 winter season and has operated during the following winter seasons: 1988-1993, 1994-95, and 2000 to the present. One other program has developed to target the south slopes of the High Uinta Mountains located in two northeastern Utah counties (Duchesne and Uintah). This program began during the 2000-01 winter season and has continued to the present.

There have been other short duration programs conducted in other parts of the State. For example, there was a program conducted for a few winter seasons to affect the La Sal Mountains located in southeastern Utah. Figure 2 provides the locations of all historical cloud seeding programs since 1974.

2. ORGANIZATION

The cloud seeding programs are supported at the county or multi-county level. A non-profit group, Utah Water Resources Development Corporation, was organized to represent a number of the central and southern Utah counties. County Commissions or Water Conservancy Districts represent each of the counties that participate. A commitment is made each fall by these counties or conservancy districts to conduct a program for the approaching winter season.

All of these programs have received cost sharing support from the Utah Division of Water Resources since 1976. The typical portion of the costs funded by the State in recent years has ranged from 37 to 50% of the total program costs. Figure 3 provides the amount of State and local funding support since 1974. Figure 4 provides the participation by Utah counties since the beginning of the winter cloud seeding programs in 1974.

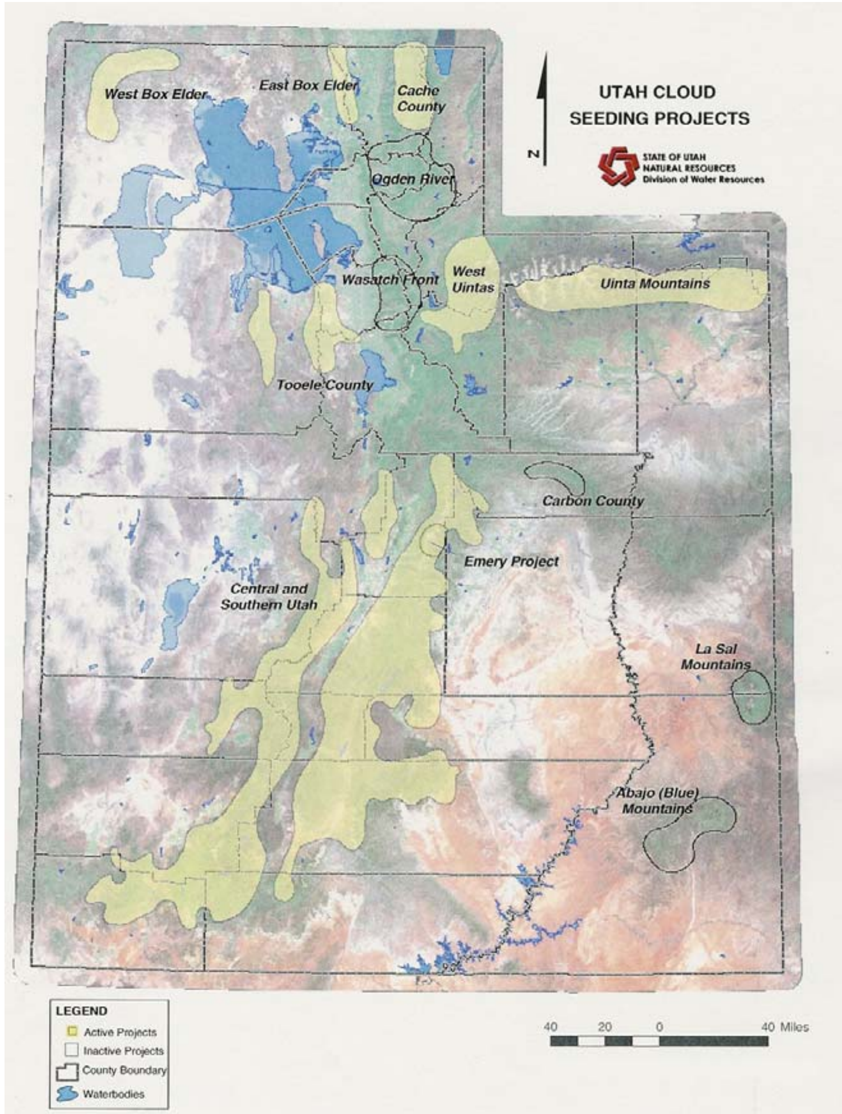

Figure 2 Current and Historical Utah Cloud Seeding Programs

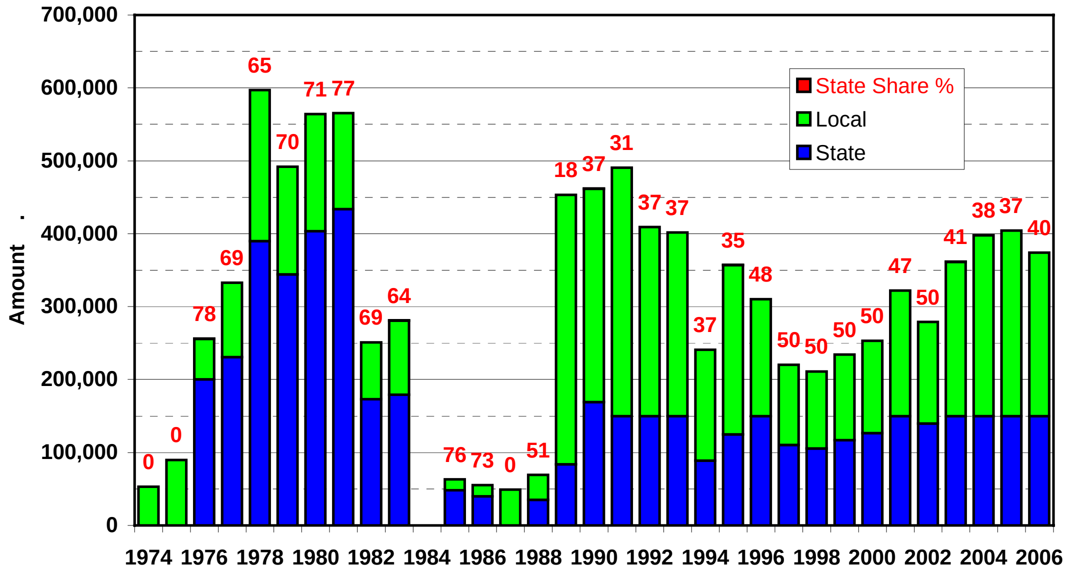

Figure 3 State and Local Funding of Utah Cloud Seeding Programs, 1974-2006

County	73-74	74-75	75-76	76-77	77-78	78-79	79-80	80-81	81-82	82-83	83-84	84-85	85-86	86-87	87-88	88-89	89-90	90-91	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01	01-02	02-03	03-04	04-05	05-06	06-07
Beaver	x	x	x	x	x	x	x	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Emery	x	x	x	x	x	x	x	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Garfield	x	x	x	x	x											x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Iron	x	x	x	x				x	x	x							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Juab	x	x	x	x	x	x	x	x	x	x							x						x	x	x	x	x	x	x	x	x	x	x	x
Millirad	x	x	x	x	x	x	x	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Piute	x	x	x	x	x	x	x	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
San Juan			x	x	x	x	x	x	x	x							x	x	x	x														
Sanpete	x	x	x	x	x	x	x	x	x	x					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Sevier	x	x	x	x	x	x	x	x	x	x								x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Tooele			x	x	x	x	x	x	x	x							x	x	x				x	x	x	x	x	x	x	x	x	x	x	x
Washington	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Wayne	x	x	x	x	x	x	x	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Kane	x	x																																
Grand					x	x	x	x	x	x							x																	
Carbon					x	x	x	x	x	x							x																	
Duchesne				x	x											x														x	x	x	x	x
Uintah				x	x											x														x	x	x	x	x
Daggett				x	x											x																		
Davis				x																														
Weber				x														x	x	x														
Salt Lake				x											x	x	x	x	x	x	x	x	x											
Morgan				x														x	x	x														
Summit				x												x	x	x	x	x		x						x	x	x	x	x	x	x
Utah				x																														
Box Elder																x	x	x	x	x	x	x	x	x			x	x			x	x	x	x
Cache																x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Rich																	x	x																
Wasatch				x												x	x	x	x	x		x						x	x	x	x	x	x	x

Figure 4 Cloud Seeding Program Participation by Utah Counties by Year

3. SCIENTIFIC BASIS

The Utah programs were originally designed based upon results obtained from research oriented weather modification programs in the western United States conducted in the 1960's through 1980's (e.g., Climax I and II, the Colorado River Basin Pilot Project, and the Bridger Range Experiment). Designs were updated based upon results obtained from more recent research programs such as the Utah NOAA Atmospheric Modification Program (1990 - 1998). Research funded under the Utah NOAA AMP program was conducted in two different areas in Utah, the Tushar Mountains located in south central Utah and the Wasatch Plateau located in central Utah.

4. CONCEPTUAL MODEL

The basic conceptual model upon which the Utah seeding programs is based can be summarized as follows:

Some winter storms or portions of naturally occurring winter storms that pass over Utah contain/produce supercooled water droplets. Some of these droplets are not converted to ice crystals as they pass over the mountainous areas of Utah. The presence of supercooled water droplets over the crests of these mountain barriers indicate that these storms or portions of storms are inefficient in the production of precipitation. This inefficiency is attributed to the lack of enough natural ice nuclei (also called freezing nuclei) to covert these supercooled water droplets to ice crystals which, given the right conditions, could develop into snowflakes that would fall on the mountain barriers. The deficit in natural ice nuclei occurs primarily in the range of cloud temperatures in the 0C to –15C range. Introduction of artificially generated silver iodide particles into cloud systems that contain supercooled water droplets in approximately the –5 to –15C range will artificially nucleate some of the supercooled water droplets. The –5C temperature is considered the nucleation threshold of silver iodide. The resultant ice crystals then have the potential to grow into snowflakes through vapor deposition and riming processes. If the ice crystals are generated in the right geographic locations, the artificially generated snowflakes will fall onto the targeted mountain barriers, resulting in increases in precipitation above what would have occurred naturally.

Research conducted in Utah and other intermountain west locations (e.g., Super, 1999; Reynolds, 1988) have verified the presence of supercooled water droplets near or over mountain barrier crests in a large number of winter storm periods. Research in a variety of locations has indicated the background concentrations of ice nuclei are low in the warmer portions of the atmosphere but increase exponentially at colder temperatures. Research efforts conducted in cloud chambers and in the atmosphere have demonstrated the ability of silver iodide nuclei to serve as ice nuclei in significant concentrations beginning near the –5C level and increasing exponentially to the –20 to –25C level.

5. PROGRAM DESIGN

The program design is based upon the results obtained from previous research programs in which these results are felt to be transferable to Utah and implementation is based on methods that are compatible with the conceptual model. Seeding relies upon the use of ground based seeding, although some airborne seeding was attempted during a few winter seasons. Key problems encountered with airborne seeding were the relatively high altitudes (approximately 4.3 km, 14,000 feet MSL) aircraft had to be flown based upon FAA approved routes and the difficulty in effectively covering the large Utah target areas even with multiple aircraft. It was theorized that seeding plumes released at these higher altitudes would miss the supercooled liquid water regions that research in Utah and California indicated to be predominantly located over the upwind slopes of mountain barriers at low elevations (perhaps only extending to 0.15 to 0.3 km, 500-1000 feet above the mountain crests). An analysis of one winter of seeding in southern Utah when there were four seeding aircraft available suggested that a seeding aircraft was upwind of a ground station that was reporting precipitation only about 10% of the time.

5.1 Silver Iodide Generators

The operational winter cloud seeding programs in Utah rely upon the release of silver iodide nuclei from strategically placed, manually operated ground generator sites located in valley or foothill locations (see Figure 5). These generators contain a 3% solution of silver iodide complexed with sodium iodide and paradichlorobenzene dissolved in acetone that is burned in a propane flame. The emission rate of silver iodide is approximately 12 grams per hour. Sodium iodide and paradichlorobenzene are added to the seeding solution based upon results from tests performed in the Colorado State University cloud chamber. A paper published by Finnegan (1999) indicates that this formulation is superior to others that produce pure silver iodide particles. The modified particles produced by combustion of the revised formulation act as ice nuclei much more quickly (probably through a condensation-freezing mechanism), and there are somewhat larger numbers of effective nuclei at warmer temperatures (e.g., about -5 to -10C). Figure 5 provides a photograph of one of these manually operated ground-based generators.

Figure 5 Manually Operated Silver Iodide Generator

Some would argue for higher elevation, remotely operated ground based generators to be used on these Utah programs. In a strictly technical sense this approach would seem to have merit, based primarily on the concern that effluent released from lower elevation sites might become trapped by low-level atmospheric conditions (e.g., inversions). There are a number of considerations important in this discussion; we will touch on a couple of the more important ones: economics, feasibility, and observations.

NAWC has 148 manually operated ground generators installed for the 2007-2008 winter season in Utah (for locations refer to Figure 6). The cost of remotely controlled ground generators is approximately $40,000 each without any consideration of installation or maintenance costs. A network of 148 remotely controlled generators that would match the number of NAWC's lower elevation generators would cost approximately $5,920,000 just to cover the acquisition costs. There are additional complications regarding the implementation of a large, remotely controlled generator network. Suitable sites must be found and leases arranged for these locations. Often, these suitable sites will lie on National Forest or Bureau of Land Management lands which may well make the approval for such use problematic. Remote locations may require over the snow or helicopter servicing during the winter, which can be an expensive proposition.

Analyses of observations from the Utah NOAA AMP research program indicated that valley released silver iodide plumes might be trapped in lower elevations 37% of the time based upon an analysis of 46 rawinsonde observations collected during three winter seasons. The critical missing information in this analysis was how often supercooled water droplets were occurring over the mountain barrier during these periods. In other words, the trapping of silver iodide under these conditions may have frequently been in pre-frontal conditions with little seeding potential. This supposition on our part receives strong support from this same Utah research program which indicated from an analysis of 100 hours of data from seven relatively wet storms in which supercooled liquid water was present and several of NAWC's lower elevation generators were being operated that silver iodide was present over the targeted mountain barrier 90% of the time. The following statement was made in this paper "This is remarkable when it is realized that valley-based inversions are common during winter storms.

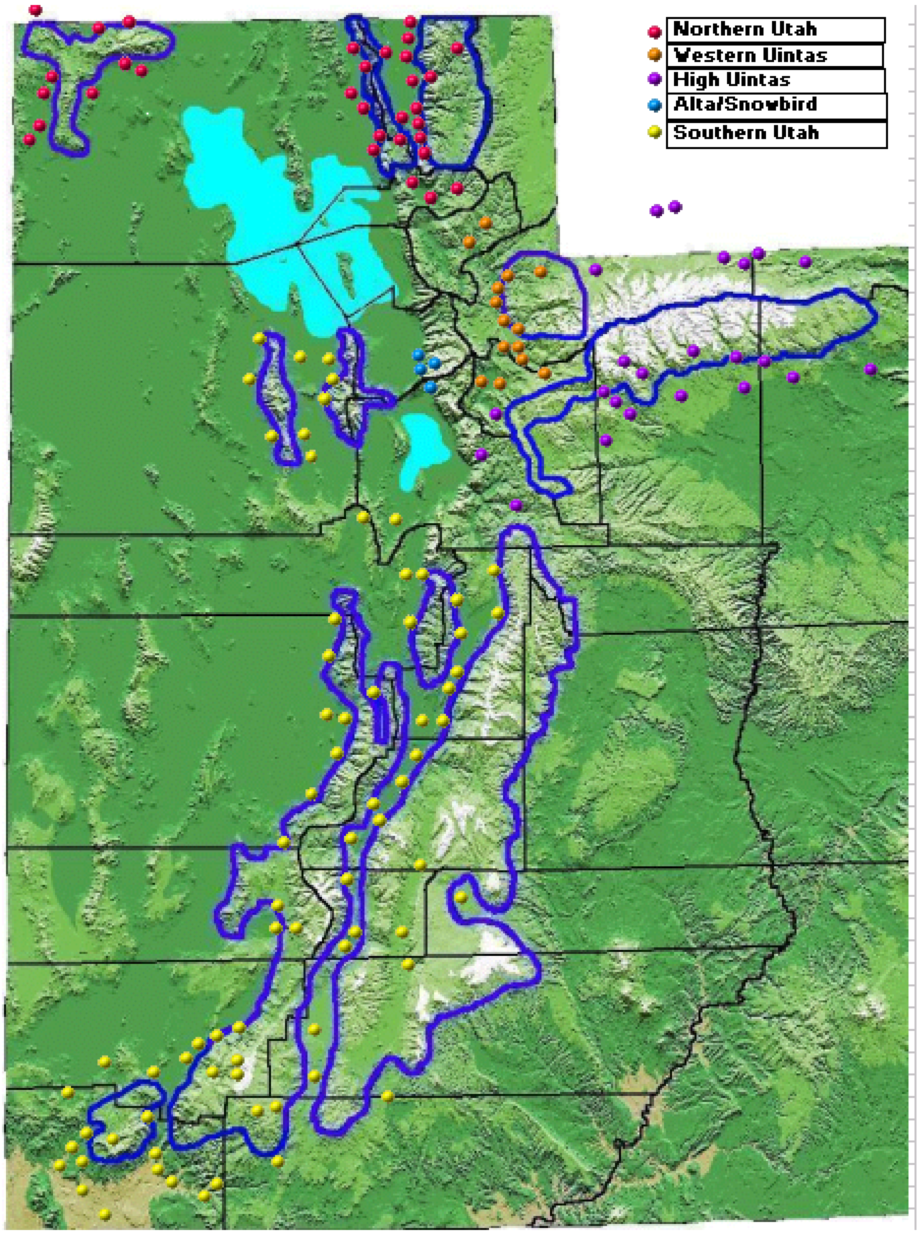

Figure 6 2007-2008 Active Target Areas and Generator Locations

However, most hours with supercooled liquid water amounts of 0.05mm or greater had weak embedded convection present, which likely assisted vertical silver iodide transport."

We do agree that cloud seeding from remotely controlled ground generators may be more effective under certain conditions, but the cost of implementing a large remotely controlled ground generator network to impact the large target areas in Utah is not practical in the economic sense. The design of programs using remotely controlled ground generators for smaller target areas, in Utah or elsewhere, where the resultant water has significant value (say, greater than several hundred dollars per acre-foot) may be justified. Water in Utah for agricultural purpose is worth perhaps $10-15 per acre-foot and perhaps $50 to a few hundred dollars per acre-foot for municipal water supplies (Utah State Water Plan, 2001). Contrast these values with municipal water in parts of California, which may be worth several hundred dollars to near $1000 per acre-foot (California State Water Plan, 2005).

5.2 Generalized Seeding Criteria

NAWC has developed some generalized seeding criteria for the use of our meteorologists in deciding whether a specific weather event should be considered potentially seedable. These criteria consider two basic questions:

1. Is it likely that supercooled liquid water is present?
2. Can some of the installed generators be used to effectively target this seeding potential?

Table 1 provides these generalized seeding criteria.

Table 1

NAWC Winter Orographic Cloud Seeding Criteria

1)	CLOUD BASES ARE BELOW THE MOUNTAIN BARRIER CREST.
2)	LOW-LEVEL WIND DIRECTIONS AND SPEEDS THAT WOULD FAVOR THE MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THEIR RELEASE POINTS INTO THE INTENDED TARGET AREA.
3)	NO LOW LEVEL ATMOSPHERIC INVERSIONS OR STABLE LAYERS THAT WOULD RESTRICT THE VERTICAL MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THE SURFACE TO AT LEAST THE -5°C (23°F) LEVEL OR COLDER.
4)	TEMPERATURE AT MOUNTAIN BARRIER CREST HEIGHT EXPECTED TO BE -5°C (23°F) OR COLDER.
5)	TEMPERATURE AT THE 700 MB LEVEL (APPROXIMATELY 10,000 FEET) EXPECTED TO BE WARMER THAN -15°C (5°F).

5.3 Suspension Criteria

Cloud seeding suspension criteria have been developed between the Utah Division of Water Resources and NAWC. These criteria are primarily concerned with:

1. Rain-induced winter floods.
2. Excess snowpack accumulations.

The potential for wintertime flooding from rainfall on low elevation snowpack is fairly high in some of the more southern target areas during the late winter/early spring period. Every precaution must be taken to insure accurate forecasting and timely suspension of operations during these potential flooding situations. The objective of suspension under these conditions is to eliminate both the real and/or perceived impact of weather modification when any increase in precipitation has the potential of creating or adding to a flood hazard.

Snowpack begins to accumulate in the mountainous areas of Utah in November and continues through April. The heaviest average accumulations normally occur from January through March. Excessive snowpack becomes a potential hazard from snowmelt. The Natural Resources Conservation Service (NRCS) maintains a network of high elevation snow pack measurement sites in the State of Utah. This network is known as SNOTEL. SNOTEL observations are routinely available at several times per day. The following set of criteria, based upon observations from these SNOTEL site observations, has been developed as a guide for suspension of operations.

- 200 % of average on January 1 st
- 180 % of average on February 1 st
- 160 % of average on March 1st
- 150 % of average on April 1st

These suspensions are determined on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne River, Price-San Rafael, Dirty Devil, South Eastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. Since SNOTEL observations are available on a daily basis, suspensions (and cancellation of suspensions) can be made on a daily basis using linear interpolation of the first of month criteria.

Streamflow forecasts, reservoir storage levels, soil moisture content and amounts of precipitation in prior seasons are other factors which are considered when suspending seeding operations.

These suspension criteria have been invoked for varying periods over the years. One of the more notable events occurred in early January 2005 when seeding was suspended due to the excess snowpack criteria. A few days later a warm, heavy rain event impacted southern Utah. This rain on snow event resulted in flooding near St. George, Utah. Rather vivid video showed entire homes falling into the Santa Clara River near St. George due to this flooding. Had excess snowpack criteria not have been exceeded; seeding would still have been suspended on this storm system due to the rain-induced winter floods criteria. Suspensions continued in a large portion of southern Utah during the latter part of the 2005 winter season due to the snowpack suspension criteria.

6. PROGRAM OPERATIONS

An array of information available via the internet is used to make real-time seeding decisions to determine whether to operate and, if so, which generators to activate. Types of data or analysis utilized include: weather satellite visual and infra-red photos, surface and upper-air analyses (especially those at the 700 mb level), rawinsonde skew-t plots, surface observations, video cameras, weather radar displays, weather forecasts and weather forecast model output, NRCS SNOTEL observations (temperature, precipitation). The project meteorologist considers this information to determine if the generalized seeding criteria are met and that no suspension criteria are met, and then determines which generators are to be operated primarily as a function of low-level winds that determine the targeting of the seeding effects. Different generators may be operated as the winds change with the passage of the storm through the target area.

7. PROGRAM EVALUATIONS

Evaluations of the effects of operational cloud seeding programs are rather challenging. Since program sponsors wish to derive the maximum potential benefits from a cloud seeding program, operations are directed at seeding every potentially seedable event. Operational program sponsors are typically unwilling to employ some form of randomization of seeding decisions, which could assist in evaluating the effects of seeding, since their desire is to maximize the beneficial effects of the seeding. Essentially these sponsors have sufficiently high confidence that cloud seeding can produce positive effects to warrant moving ahead with an operational program. They generally do not see the necessity of conducting a program to “prove” that the cloud seeding is “working” as would be one of the primary goals in the conduct of a research program.

The above is not to say that sponsors of operational cloud seeding programs are not desirous of having a reasonable indication that the program is working. This indication need not be as rigorous as that from a research program where a 5% or better significance level attached to any indicated results is required. Sponsors of operational programs are accustomed to dealing with much more uncertainty than this on almost a daily basis.

What types of evaluations then can potentially be applied to operational programs? There are three basic categories of possible evaluation techniques:

1. Statistical Approaches
2. Physical Approaches
3. Modeling Approaches

7.1 Statistical Approaches

One commonly employed statistical technique is the "target" and "control" comparison. This technique is one described by Dr. Arnett Dennis in his book entitled “Weather Modification by Cloud Seeding” (1980). This technique is based on selection of a variable that would be affected by seeding (e.g., liquid precipitation, snowpack or streamflow). Records of the variable to be tested are acquired for an historical (not seeded) period of many years duration (20 years or more if possible). These records are partitioned into those located within the designated "target" area of the project and those in a nearby "control" area. Ideally the control sites should be selected in an area meteorologically similar to the target, but one that would be unaffected by the seeding (or seeding from other adjacent projects). The historical data (e.g., precipitation) in both the target and control areas are taken from past years that have not been subject to cloud seeding activities in either area. These data are evaluated for the same seasonal period as that of the proposed or previous seeding. The target and control sets of data for the unseeded seasons are used to develop an equation (typically a linear regression) that estimates the amount of target area precipitation, based on precipitation observed in the control area. This regression equation is then applied to the seeded period to estimate what the target area precipitation would have been without seeding, based on that observed in the control area(s). This allows a comparison between the predicted target area natural precipitation and that which actually occurred during the seeded period, to determine if there are any differences potentially caused by cloud seeding activities. This target and control technique works well where a good historical correlation can be found between target and control area precipitation. Generally, the closer the target and control areas are in terms of elevation and topography, the higher the correlation will be. Control sites that are too close to the target area, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, a correlation coefficient (r) of 0.90 or better would be considered excellent. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set would be explained by the regression equation used to predict the variable (expected precipitation or snowpack) in the seeded years. An equation indicating perfect correlation would have an r value of 1.0.

7.2 Physical Approaches

The results from a statistical evaluation, such as a target/control analysis, can be strengthened through supporting physical studies, as recommended in a response to a National Research Council Report (2003) by the Weather Modification Association (WMA, 2004). One technique that has been employed by the Desert Research Institute (DRI) in the assessment of the effectiveness of at least the targeting (if not the magnitude) of seeding effects of winter programs is that of analyzing samples of snow from the target area during seeded periods to determine whether silver is present in projects that use silver iodide as the seeding agent (Warburton, et al, 1995 and 1996). The following contains a summary of this technique.

Occasionally, samples of newly fallen snow are collected for an analysis of silver content. This is an evaluation technique encountered more frequently in research projects due to the expense involved. Snow samples collected prior to cloud seeding or from non-seeded storms are analyzed to establish the natural background silver content (if measurable with available analysis techniques) for comparison with snow samples taken from seeded storms. This technique is only valid for projects using silver iodide as the cloud seeding agent, although some analysis techniques are applicable to other possible cloud seeding agents as well (e.g, lead iodide). Several analysis techniques have been developed for use in such analyses, including neutron activation, proton excitation, and flameless atomic absorption. An example of an analysis of the downwind transport of silver iodide outside of primary target areas is given by (Warburton 1974). Warburton et al, 1996 demonstrates how trace chemical assessment techniques strengthen traditional target and control precipitation analyses.

7.3 Modeling Approaches

Sophisticated atmospheric computer models have the potential to estimate the amounts of natural precipitation for short intervals (e.g., 6 hours, 12 hours) in mountainous areas. <u>If</u> these predictions are validated as accurate, they could be compared with the amount of precipitation that fell during seeded periods within the intended target area to determine the impact of seeding on target area precipitation. An attempt to verify the output of the RAMS computer model developed at Colorado State University versus observed and predicted modified precipitation due to cloud seeding was made for the 2003-2004 winter season in central Colorado, with rather mixed results. This work was done under the Colorado WDMP. Some of the conclusions from the final report (Colorado Water Conservation Board, 2005) are:

- When model simulated precipitation was compared to measured 24-hour precipitation at 61 SNOTEL sites the model exhibited a mean precipitation bias of 1.88.
- Comparison of model-predicted precipitation (control) versus seeded precipitation revealed that there was essentially no difference between the 86-day seed and control average totals.

The report listed the following possible reasons for the lack of differences between seed and control precipitation:

- The model-predicted seedability could be real; however, because of the model over prediction bias and low amounts of supercooled liquid water content, this possibility is doubtful.
- There is circumstantial evidence that the model-predicted supercooled liquid water content is too low, thereby underestimating seedability.
- A low-level warm temperature bias in the model results in delayed AgI nuclei activation and reduced effectiveness of the seeding agent in the model.

Wyoming is using a state-of-the art high-resolution model known as WRF for guidance and evaluation of their five-year pilot cloud seeding research project. It has not been demonstrated, even with this model, whether simulations are sufficiently accurate to discern seeding effects from natural precipitation, or even to accurately predict the transport and dispersion of seeding material.

7.4 NAWC Evaluations

NAWC has frequently utilized the first of these approaches (statistical) in evaluating the apparent effects of our operational programs. Two types of data are normally used in developing these equations relating target and control areas: 1) some accumulation of monthly precipitation data representative of the seeded period (e.g., December through March), and 2) April 1st snow water content. The agency that has collected the most useful data is the Natural Resource Conservation Service (formerly the Soil Conservation Service).

Data are obtained from possible target and control stations. Some quality control procedures are employed to determine whether some sites should be dropped due to missing data or movement of stations causing a change in the observations. Control sites are selected to avoid including sites that may have been impacted either historically or currently by other cloud seeding programs. Data are averaged for the potential target and control sites and linear regression techniques are applied to the data. The goal is to find the mix of possible control sites that provide the highest correlation with the target sites.

As an example, Figure 7 provides the locations of target and control stations that have been used for a number of years in the evaluations of the central/southern Utah program. The linear regression equation relating the target and control areas for this program is: $y = 1.66x - 2.79$ where y is the predicted average target area December through March precipitation and x is the control station average December through March precipitation. The r^2 value for this regression equation is 0.92. Table 2 summarizes the indications of seeding effects on the on-going, longer-term Utah seeding programs. An earlier evaluation of the December through March precipitation indicated the same apparent 14% increase as now shown in Table (Griffith, et al, 1991). Figure 2 provides the locations of the various target areas.

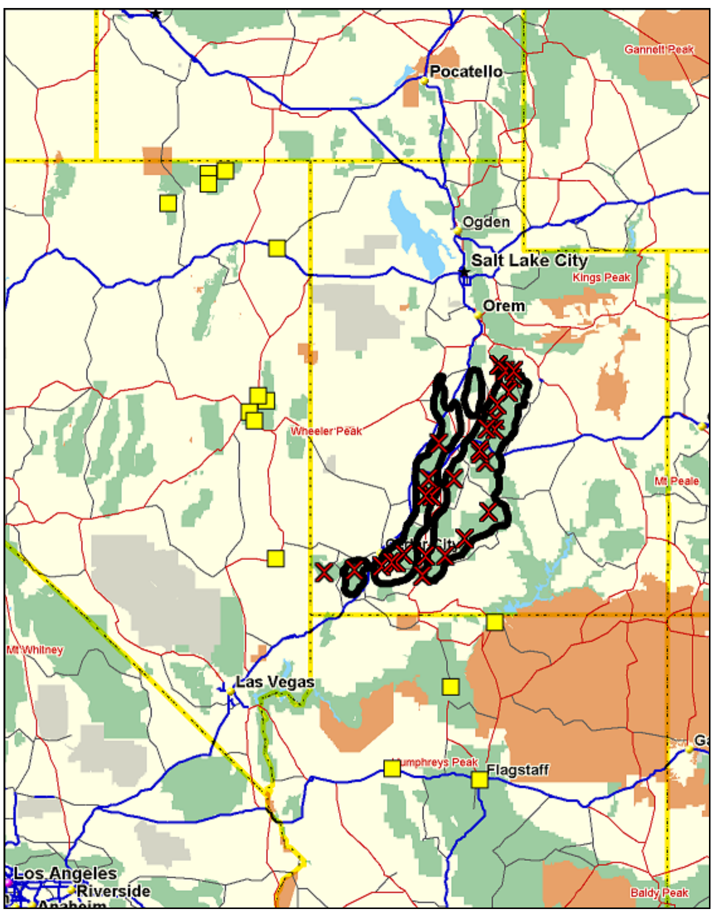

Figure 7 Precipitation Target Sites (red x's) and Control sites (yellow squares)

Table 2 Summary of Historical Target/Control Evaluations of Various Target Areas in Utah

Target Area	Number of Seasons	Precip. r^2 value	Precip. %	Precip. Difference (inches)	Snow Water r^2 value	Snow Water %	Snow Water Difference (inches)
NW Box Elder	15	----	---	---	.83	+17	2.6
E. Box Elder Cache	19	.81	+17	2.1	.83	+10	2.2
E. Tooele	23	.74	+21	1.8	.68	+16	2.0
Western Uintas	13	.75	+5	0.6	.77	+5	0.8
South Slope High Uintas	5	.89	+3	0.4	.65	+3	0.4
Central/ Southern	29	.92	+14	1.4	.87	+4*	0.6

* NAWC's annual project report for the 2003-2004 winter season indicated that a change (reduction) in indicated results was due to our decision to use NRCS adjusted snow water content data in this evaluation. The precipitation evaluations are considered more representative for this target area.

The range of indicated seeding effects from Table 2 for precipitation is 3-21% and 3-17% for April 1st snow water content. Lower percentages in the Uinta Mountain programs may be due to possible impacts of pollution from the Salt Lake City/Provo complex. Pioneering work by Dr. Rosenfeld (2000) demonstrated that winter orographic precipitation downwind of major metropolitan areas in Israel and the western United States has been declining. NAWC conducted a study similar to those conducted by Dr. Rosenfeld to determine if similar impacts were occurring downwind of the Salt Lake City/Provo complex (Griffith, et al, 2005). This study did indicate a decline in winter precipitation in the western end of the Uinta Mountains, which are located east of Salt Lake City. Figure 8 provides a plot from this study that demonstrates this decline at the Trial Lake NRCS SNOTEL site. This site sits on a divide between two cloud seeding programs (western Uintas and south slope of the High Uintas). The study documented how this decline in precipitation could reduce the indicated effectiveness of the seeding programs in this area. Other more rural areas of the State were analyzed in this study. Declines in winter mountainous precipitation in these areas were not observed. It was therefore concluded that the estimated seeding effects in other areas of the State would not be impacted like those downwind of Salt Lake City.

Figure 9 is provided as an example of the apparent consistency in positive seeding effects for December through March precipitation in the central/southern program. This figure provides a plot of the ratios of the actual divided by the predicted precipitation for the historical, not-seeded seasons (18) and for the seeded seasons (30). This figure indicates that only 2 of the 30 seeded seasons had ratios less than 1.0. In other words, 28 out of 30 seasons have indications of a positive seeding effect.

A recurring question regarding cloud seeding programs is whether the cloud seeding program is reducing precipitation downwind of the intended target area? This question is sometimes referred to as whether you are "Robbing Peter to pay Paul." NAWC attempted to answer this question regarding one of the Utah winter programs. The program selected for analyses was the central/southern Utah program since it is the region with the longest period of cloud seeding activities within the state. The same target/control regression technique applied to an evaluation of the central/southern target area was used to examine predicted versus observed December through March precipitation in areas downwind of the intended target area. This downwind area included precipitation observation stations located in southeastern Utah and southwestern Colorado. Figure 10, taken from a paper summarizing this analysis (Solak, et al, 2003), provides ratios of observed to predicted precipitation during 25 seeded seasons. Ratios greater than 1 (which are widespread in the figure) suggest increases in precipitation in this downwind area, contrary to the often stated concern that precipitation would be less in such a downwind location. Table 3, taken from the referenced paper, demonstrates the apparent seeding effects in the downwind area as a function of distance from the intended target area. This table indicates that apparently positive seeding effects extend downwind for approximately 100 miles. It should be noted that

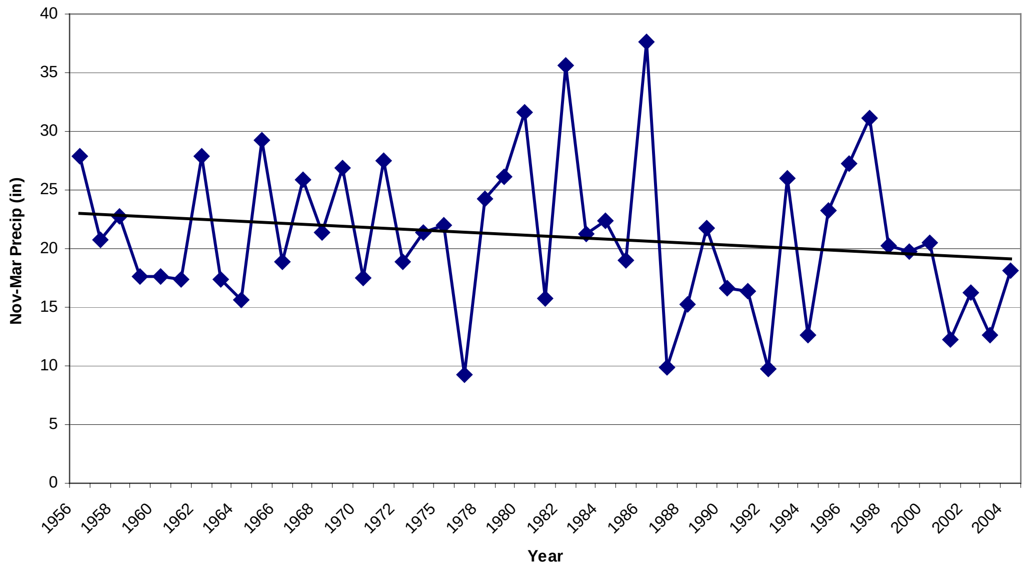

Figure 8 Plot of November – March Precipitation at Trial Lake, Utah (1956-2004, excluding 1973 and 1976)

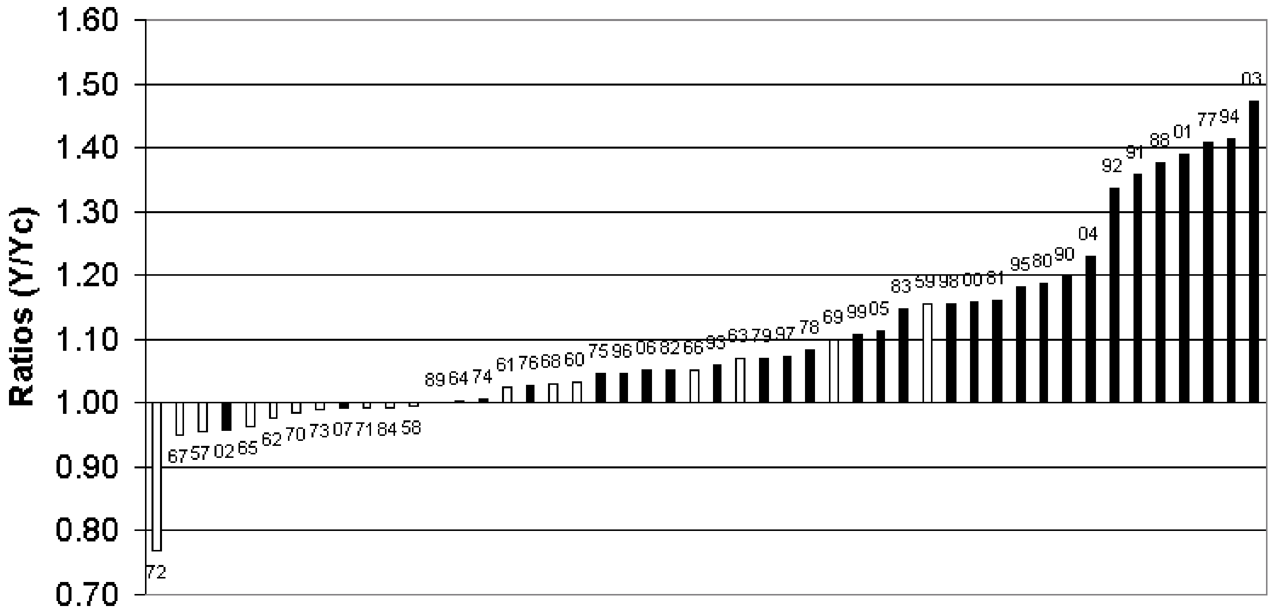

Figure 9 Plot of December-March Actual Precipitation Divided by Predicted Precipitation. Open bars are historical seasons, solid bars are seeded seasons.

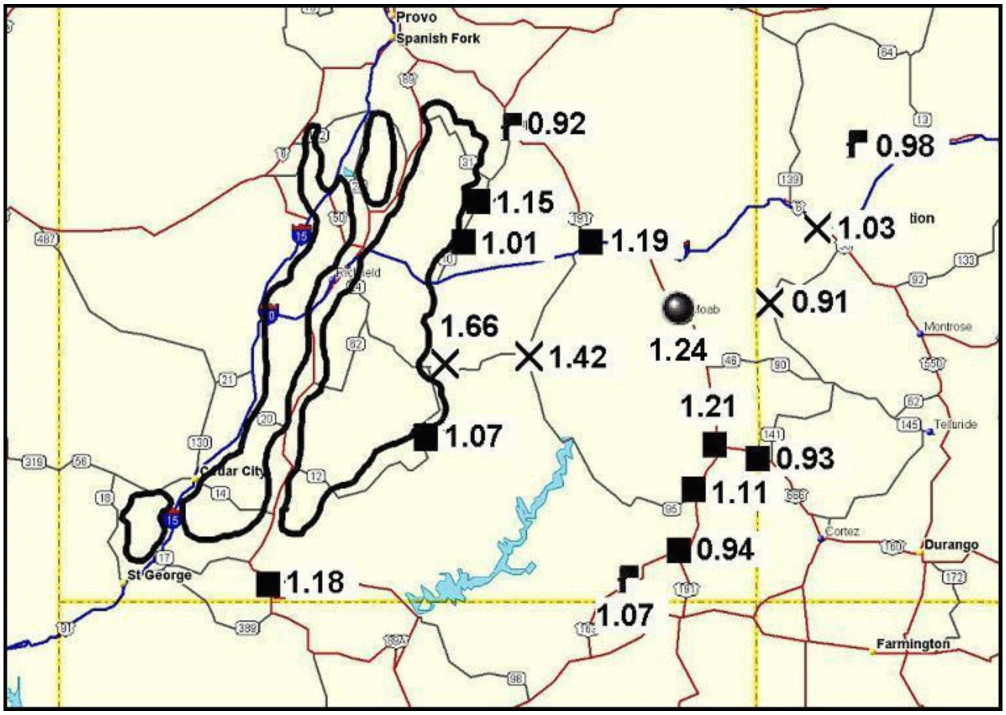

Figure 10 Individual site ratios for seeded seasons. (Central/Southern Target Area Outlined in Black)

Table 3 Results of grouping data into 50-mile-wide downwind distance bands

Distance From Target	No. of Sites	Ratio 0bs/Pred	Precip. Diff. (in.)	Correlation (r)
Seeding Target	27	1.14	1.39"	0.97
0-50 miles	7	1.14	0.38"	0.91
50-100 miles	3	1.17	0.34"	0.82
100-150 miles	7	1.03	0.10"	0.91

even though the ratios found in Figure 10 suggest apparent increases in downwind precipitation on the order of an average of 10-15%, the actual amounts of increased precipitation are relatively low since southeastern Utah is an area that naturally receives low amounts of precipitation.

8. ESTIMATED INCREASES IN STREAMFLOW

Dr. Norman Stauffer of the Utah Division of Water Resources reported on some work he had conducted in an attempt to estimate increases in streamflow that could be generated by the estimates of increases in April 1st snow water content attributed to cloud seeding (Stauffer and Williams, 2000). The procedures used to make these estimates were as follows:

1. Estimate the average annual runoff from the areas that are being seeded (target areas).
2. Estimate the increase in April 1st snow water content attributed to seeding.
3. Determine the relationship (equations) between annual runoff and April 1st snow water content for major gaged rivers and streams in the target areas.
4. Estimate the increase in average annual runoff due to cloud seeding, based on 1, 2, and 3 above.

The Stauffer study focused on four target areas that were active during the 1999-2000 winter season. The areas were: western Box Elder County, Eastern Box Elder and Cache Counties, Eastern Tooele County, and central/southern Utah. Refer to Figure 2 for the locations of these four areas. This analysis estimated the average annual increase in streamflow from these seeded areas to be 249,600 acre-feet. The resulting cost (for WY 2000) was $1.02 per acre foot.

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