A WINTER OPERATIONAL CLOUD SEEDING PROGRAM: UPPER GUNNISON RIVER BASIN, COLORADO

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Abstract: A winter orographic cloud seeding program has been conducted in the Gunnison, Colorado region for the past eight winter seasons. The intended target area is elevations above 9,000 feet MSL that provide streamflow to Blue Mesa Reservoir located in western Gunnison County. The goal of this operational program has been to augment higher elevation winter snowpack, which subsequently contributes to spring and summer streamflow. This program has operated under permits granted by the Colorado Water Conservation Board. The program is supported by a number of local entities and it has also received some funding support from the Colorado Water Conservation Board and the three Lower Colorado River Basin States (Arizona, California and Nevada). A network of 20-25 ground based silver iodide generators has been used to seed all storm periods thought to represent good seeding opportunities based upon targeting considerations and the likely presence of supercooled liquid water. An historical target/control evaluation technique was developed, based upon NRCS SNOTEL April 1st snow water content observations, to provide estimates of the potential effects of cloud seeding. These estimates indicate average seasonal increases in the 10-15% range. Calculations were made of increases in April through July streamflow based upon the indicated increases in April 1st snow water contents. Increases in the range of 79,600 to 96,200 acre-feet in an average April – July runoff were indicated based upon a 10% increase in April 1st snow water content for an average winter season. Costs of producing the augmented runoff based upon these calculated increases in streamflow ranged from $0.94 to $1.13 per acre-foot.

1. INTRODUCTION AND BACKGROUND

The Gunnison County Manager contacted North American Weather Consultants (NAWC) in the fall of 2002 about the possibility of establishing a cloud seeding program in Gunnison County. Gunnison County is located in west central Colorado. The initial interest was in a program to benefit the Crested Butte Ski area but discussions lead to the consideration of a program to enhance the snowpack in the higher mountainous areas of Gunnison County in order to augment spring and summer streamflow. An RFP was issued to prepare a design, operate and then evaluate such a program. NAWC was awarded the contract and operated a partial program during the 2002-2003 winter season. Annual contracts were then awarded to NAWC to continue this program each winter season through the current 2010-2011 winter season. The design, operation and evaluation of this program are discussed in subsequent sections.

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The State of Colorado maintains regulations that govern cloud seeding activities conducted in the state. These regulations are administered by the Colorado Water Conservation Board (CWCB). A summary of this process from the CWCB website is as follows: "A permit is required to modify the weather in Colorado. Cloud seeding contractors must work with local interests to develop an operational plan and funding for a cloud seeding project. The contractor then can apply for a permit to cloud seed from the State of Colorado on behalf of the project sponsors. The person managing the project must be qualified. Public hearings are conducted, a record of decision is developed, and if issues can be resolved and/or addressed, the CWCB director signs the permit." NAWC fulfilled the requirements of these regulations and was granted a permit on February 3, 2003. This permit was valid for a five-year period. Sponsors of the program requested that NAWC apply for a separate permit during the summer of 2003 to expand the intended target area to include high elevation areas in adjoining counties that provide streamflow to the Gunnison River above Blue Mesa Reservoir. NAWC complied with this request and was granted another five-year permit to include those areas on November 16, 2003. Since the first permit expired on April 15, 2007, NAWC applied for a new permit that consolidated the target areas. This new five-year permit was granted on November 16, 2007. Figure 1 shows the location of the Gunnison River Basin, which is located in western Colorado. Blue Mesa Reservoir is shown in this figure west of the city of Gunnison in the upper Gunnison River Basin.

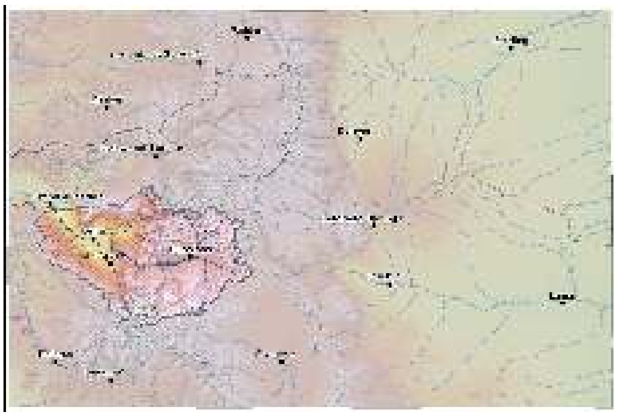

Figure 1: Gunnison River Basin.

2. PROGRAM ORGANIZATION

There have been a number of local sponsors that have provided financial support to this program. These sponsors have included: City of Gunnison, Crested Butte Mountain Resort, Crested Butte South Metropolitan District, Dos Rios Water System, East River Regional Sanitation District, Gunnison County, Gunnison County Stockgrowers Association, Mt. Crested Butte Water and Sanitation District, Mt. Crested Butte, Town of Crested Butte, Scenic River Tours, and Upper Gunnison River Water Conservancy District.

Additional cost share funding to this program has been provided by the Colorado Water Conservation Board and a consortium of the three Lower Colorado River Basin States (LCRBS) of Arizona, California, and Nevada for some of the seeded winter seasons. Funds provided by the LCRBS were administered by the CWCB through a formal agreement that was implemented between the CWCB and the LCRBS. This cost sharing is summarized in Table 1.

These cloud seeding programs have been contracted and administered by Gunnison County.

Table 1. Summary of Cost Sharing by Winter Season

Winter Season	CWCB	LCRBS
2005-2006	X	
2006-2007	X	
2007-2008	X	X
2008-2009	X	X
2009-2010	X	

3. CONCEPTUAL MODEL

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

Some winter storms or portions of naturally occurring winter storms that pass over Colorado contain/produce supercooled water droplets. Some of these droplets are not converted to ice crystals as they pass over the mountainous areas of Colorado. The presence of supercooled water droplets over the crests of these mountain barriers indicates that these storms or portions of storms are inefficient in the production of precipitation. This inefficiency is attributed to the lack of sufficient natural ice nuclei (also called freezing nuclei) to convert 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 0 to –15^{0}C cloud temperatures. Introduction of silver iodide particles into cloud systems that contain supercooled water droplets in approximately the –5 to –15^{0}C range will artificially nucleate some of the supercooled water droplets. The –5^{0}C temperature is considered the nucleation threshold of silver iodide. At temperatures below approximately –15^0 C there are normally adequate numbers of natural ice nuclei to freeze the supercooled water droplets. The artificially created 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. Super and Heimbach (2005) provide a more detailed discussion of the various microphysical processes pertaining to the conceptual model as summarized in the above text.

Research conducted in Utah and other Intermountain West locations (e.g., Super, 1999; Reynolds, 1988; Solak et al., 1988 and 2005) has verified the presence of supercooled water droplets over or upwind of 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. Dennis (1980) states “the concentration of active ice nuclei increases by about a factor of 10 for each temperature drop of 3.5 to 4^{0}C. Prior research 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 –5^0 C level and increasing exponentially to the –20 to –25^{0}C level (Garvey, 1975).

4. PROGRAM DESIGN

The Upper Gunnison River Basin (UGRB) cloud seeding program was designed based upon results obtained from research oriented weather modification programs in the western United States conducted in the 1960’s through 1980’s. These programs include Climax I and II (Grant, 1986; Mielke, et al., 1981), the Colorado River Basin Pilot Project (Elliott et al., 1976), the Bridger Range Experiment (Super and Heimbach, 2009) and more recent research programs such as the Utah NOAA Atmospheric Modification Program (Super, 1999). 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 (Super, 1999). A follow-on single season randomized propane seeding experiment was conducted over a portion of the Wasatch Plateau during the 2003-2004 winter season (Super, 2005). Unfortunately, there have been no relevant research programs conducted in the United States since the late 1990’s that could be used to update the design being employed in the conduct of the UGRB program. A multi-year research program is in progress in Wyoming. The results obtained at the conclusion of that program will be examined for possible refinements to the UGRB program design.

The program design is based upon the results obtained from previous research programs in which the results are felt to be transferable to the UGRB and implementation is based on methods that are compatible with the conceptual model. The UGRB design is consistent with criteria established by the American Society of Civil Engineers (ASCE, 2004). NAWC’s initial feasibility assessment for this program was completed in 2002 (Griffith and Yorty, 2002).

The following summarize some of the findings from the initial feasibility study.

4.1 Precipitation

The Natural Resources Conservation Service (formerly the Soil Conservation Service) has been responsible for the collection and publication of precipitation information throughout the mountainous areas of the western United States. Early observations during the wintertime have included monthly manual measurements of snow water content and depth at selected locations, commonly referred to as snow surveys. In more recent years (beginning in the 1980’s), an automated system known as SNOTEL has been implemented. This system provides multiple readings of snow water content and precipitation per day. NAWC reviewed the data for Gunnison County for the period of 1990-2001. Table 2 provides the average monthly precipitation amounts (October through April) for four upper elevation sites in Gunnison County. The six-month period of November through April offers the best cloud seeding potential. October is a transition month with limited snowpack accumulation in the mountains of Colorado plus relatively warm temperatures, which limits the cloud seeding potential.

An analysis was conducted using daily precipitation records from four Natural Resources Conservation Service (NRCS) SNOTEL sites in the 9600 - 10600 foot elevation range in the mountains northwest and northeast of Gunnison, Colorado. The four NRCS sites were Brumley, Butte, Independence Pass and Park Cone. Days with approximately 0.4” or more of precipitation during the October-April season during the years from 1990 through 2001 were identified and an analysis was made of the associated meteorological conditions. There were 141 storm days identified during this eleven-year period. This analysis indicated that 12 or 13, 0.4-inch or greater storm days occurred during the

Table 2. Average Monthly Precipitation (inches)

SITE	OCT	NOV	DEC	JAN	FEB	MAR	APR
BUTTE (10160')	1.8	2.7	4.1	2.9	2.7	3.4	2.6
MC CLURE PASS (9500')	3.4	2.7	3.3	3.0	2.8	3.9	2.9
NORTH LOST TRAIL (9200')	3.4	3.2	4.2	3.2	3.4	4.2	4.3
SCHOFIELD PASS (10,700')	4.2	5.6	4.4	4.5	7.7	6.0	4.7

October-April season on average. April had the highest frequency of these events (2.7 per season), followed by November and February (2.1 per season). December had the lowest frequency with approximately one storm day per season. An average of one inch or greater amounts at these SNOTEL sites occurred on only about 10% of these storm days.

4.2 Storm Types

Over 30 of the identified storm events were analyzed to determine the weather patterns and types of storm systems likely to produce significant snowfall during the winter season. It was found that these heavier precipitation amounts occur during a variety of weather patterns, which tend to vary according to the time of year. During the winter period (December-February), many of these precipitation events resulted from strong zonal flow, with mid- and high-level Pacific moisture moving over Colorado. Satellite images during these events were often very impressive, with high cloud cover (very bright on the IR imagery) covering large portions of the western U.S. Deep upper-level trough situations were also responsible for some of the precipitation events, with storm systems over the southwestern United States and southern Rockies favoring the spring and fall seasons. Typically the more significant precipitation amounts were found to occur in southwesterly flow in advance of the surface frontal system (sometimes well in advance), although some did occur in northwesterly flow following the frontal passage. A thick shield of high-level cloud cover was evident in most of these significant precipitation events, suggesting a large amount of high-level moisture. Strong upper-level winds and a jet core near Colorado were often associated with these precipitation events.

4.3 700 mb Wind Flow and Temperature Characteristics During Storm Periods

Upper-air soundings (National Weather Service, twice daily balloon observations of temperature, dew-point and winds) from Grand Junction, Colorado (GJT) were used to determine the 700 mb (approximately 10,000') wind velocity and temperature, as well as the stability of the lower atmosphere during the 141 storm days. The 700 mb wind flow is used to represent the transport of potential seeding material, and 700 mb temperature is used to gauge the seedability of the storm events. Silver iodide, the chemical commonly used to conduct cloud seeding projects, becomes an active ice nucleant at temperatures colder than -5^0C. Winter cloud seeding research has shown that ground releases of silver iodide upwind of mountain barriers rises to heights of approximately 1500 feet above the top of the barrier depending upon atmospheric stability (Super, 1999). Therefore, the 700 mb temperature, in conjunction with the project's mean barrier height, can be used as an index of whether the silver iodide particles are likely to reach effective temperatures in a given storm.

Wind roses for the 700 mb level were prepared for all storm events combined and for individual months. The 700 mb wind rose for the October-April period is provided in Figure 2. This figure provides a plot of the frequency of the direction and speed of the 700 mb winds. The direction is reported as that from which the wind is blowing (for example, a 225^0 wind would be a wind blowing from the southwest). The 700 mb wind during these storm events strongly favored a southwesterly direction, with a direction between southerly and westerly in approximately 64% of the 166 soundings examined. The wind direction was between north and west about 23% of the time, between north and east in 8% of the soundings, and between south and east in only 5% of the soundings. March and April had the greatest variability in wind directions, but even then, when upslope storms are common on the Front Range, the Gunnison project area rarely received amounts over 0.5" from easterly-type events. November - February events occurred almost exclusively with a westerly component to the winds. Many of the soundings were dry below 650 or 700 mb. Some showed only a 100 or 200 mb thick moist layer, usually found between 500 and 700 mb. The clouds that were formed in these situations over the proposed target area were no doubt thicker than these numbers would indicate due to the forced lifting of the lower levels resulting from orographic lift over the mountain barriers.

Of the soundings examined, the 700 mb temperature was -5^0C or below slightly less than half of the time, with the overall sample average being -4.1^0C. However, the 700 mb temperature was -2^0C or colder approximately 80% of the time. Figure 3

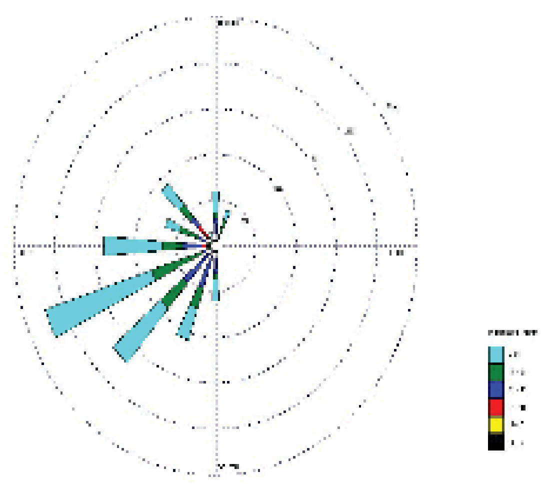

Figure 2: 700 mb Wind Rose for October- April (166 soundings).

provides a plot of the mean storm 700 mb temperature averaged by month. As expected, these average temperatures drop during the heart of the winter season. Although a –5⁰C temperature is commonly used as a maximum threshold for wintertime seeding projects, much of the Gunnison project area is above the 700 mb level (with some peaks rising to near 600 mb) and thus the seeding material can be expected to rise significantly higher than 700 mb if targeted correctly. This means that seeding is likely to be effective even when the 700 mb temperature is as warm as –2⁰ C, in which case the vast majority of these events are cold enough to be seeded via ground-based generators from the temperature standpoint.

4.4 Atmospheric Stability

Temperatures in the free atmosphere typically decrease with increasing heights. An atmospheric inversion occurs when the temperatures above the

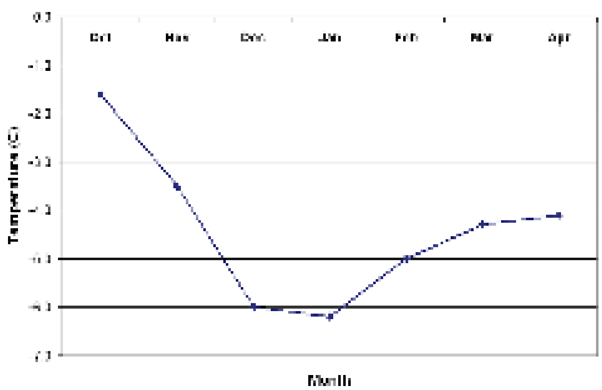

Figure 3: Mean Storm-Period 700 mb Temperature by Month.

earth's surface at a given point actually increase with height. These inversions lead to trapping of materials below the inversion. In cloud seeding applications, we are interested in knowing if atmospheric inversions or stable lapse rates (rates less than the standard lapse rate) are present in the area of interest during storm periods. If so, they will likely restrict the vertical rise of the seeding material, which may render seeding under these circumstances ineffective if the silver iodide particles do not reach the –5⁰ C level in the atmosphere.

The following analysis of lower-level stability, which utilized the balloon sounding information from Grand Junction, has some limitations since the soundings from Grand Junction are in an area of different topography from that of the project area. Stability below about 600 mb (~14,000 feet) was examined in these soundings. The atmospheric temperature profile was well mixed in 72 cases, or about 43% of the time; there were minor stable layers or slight static stability in 49 cases, or about 30% of the time; and a more definitely stable atmosphere was observed in 45 cases, or 27% of the time. The atmosphere was most stable during the month of January, with half of the soundings quite stable and over three-quarters having some stability. March and April soundings had the least stability, with over half being well mixed. Figure 4 provides a plot of this stability information by month.

4.5 Summary of Design

The information provided in the above was used to develop a seeding design for the UGRB program. The target area was defined as those areas above

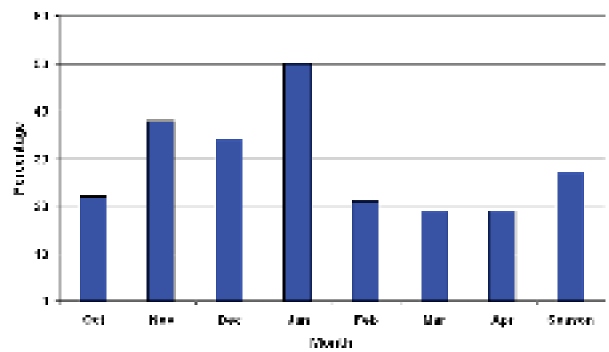

Figure 4: Percentage of Storm Events with Low-Level Inversions.

9000 feet that are tributary to Blue Mesa Reservoir. This target area is depicted in Figure 5 along with ground based silver iodide generator locations used in the conduct of the 2009-2010 operational winter season program. Different seeding modes were considered. Consideration of aircraft seeding was dropped for both technical and economic reasons. There are numerous mountain ranges located in areas upwind of the intended target barriers in the UGRB area. Numerous research studies (e.g. the Utah NOAA research program, Super, 1999) have indicated the most likely location of supercooled liquid water during winter storms in the Intermountain West will be over the upwind slopes of these mountain ranges relatively close to the terrain surface. In the situation with nearby upwind mountain barriers in the UGRB region it is difficult to safely fly aircraft under Instrument Flight Rules at low enough altitudes to impact these supercooled liquid water accumulation zones. It was decided that ground based, manually operated silver iodide generators would be used with the UGRB program based upon likely transport, stability and temperature considerations. NAWC routinely uses this seeding mode in conducting other operational programs in the west (e.g. Griffith et al., 2009). Evaluations of these programs have shown consistently favorable results. The operational period selected was November 15 to April 15 based upon the precipitation climatology of the area, plus input from the local stockgrowers whose livestock grazing may be adversely impacted by snowfall increases outside of this time period. The seeding solution used in recent years contained 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 pa-per 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).

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

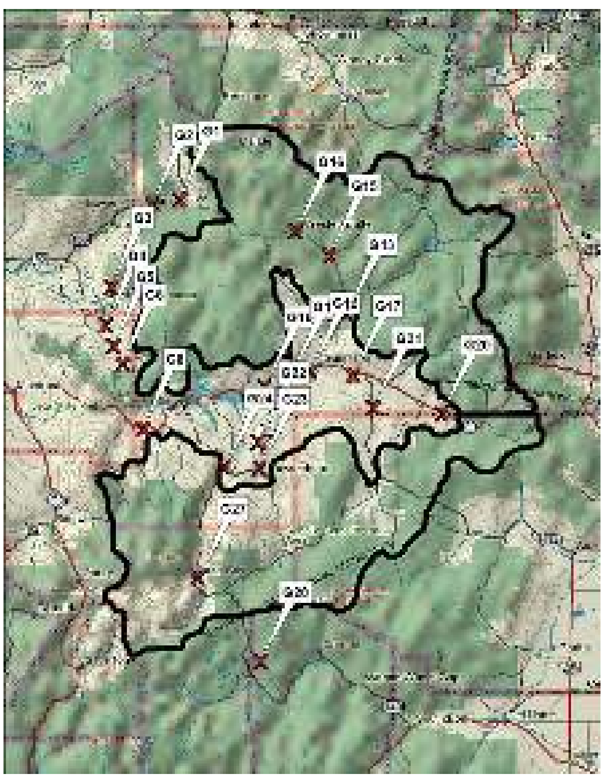

Figure 5: Upper Gunnison River Basin Target and Ground Generator Locations.

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 3 provides these generalized seeding criteria, which are used in the conduct of the UGRB program.

Table 3. NAWC Winter Cloud Seeding Criteria	
1)	Cloud bases are below the mountain barrier crest.
2)	Low-level wind directions and speeds 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 exist that would restrict the vertical movement of the silver iodide particles from the surface to at least the –50 C (230 F) level or colder.
4)	The temperature at mountain barrier crest height is -50 C (23 F) or colder.
5)	The temperature at the 700 mb level (approximately 10,000 feet) is warmer than -150 C (50 F).

Cloud seeding suspension criteria were adopted as part of the Colorado Water Conservation Board permitting process beginning with the 2002-2003 program. The suspension criteria currently in effect with the latest permit are summarized in the following. Seeding will be suspended when:

- There is any emergency that affects public welfare in the region.
- The National Weather Service (NWS) forecasts a storm to produce unusually heavy precipitation that could contribute to avalanches or unusually severe weather conditions in the project area.
- The Colorado Department of Transportation (CDOT), Colorado Avalanche Information Center (CAIC) issues daily forecasts for the populated areas within the UGRB program area. Seeding operations are suspended when the CAIC issues a “high” category rating.
- The National Weather Service forecasts a warm winter storm (freezing level > 8000 feet) with the possibility of considerable rain at the higher elevations that might lead to local flooding.
- Potential flood conditions exist in or around any of the project areas. The Permit Holder shall

consult with the NWS Flood Forecast services, and will suspend seeding if the NWS determines any of the following warnings or forecasts are in effect:

1. Flash flood warnings by the NWS.
2. Forecasts of excessive runoff issued by a river basin forecast center.
3. Quantitative precipitation forecasts issued by the NWS, which would produce excessive runoff in or around the project area.

- In addition, seeding is to be suspended at any time the snowpack water equivalents at selected target SNOTEL sites exceed:

1. 175 % of average on December 1st
2. 170 % of average on January 1st
3. 160 % of average on February 1st
4. 150 % of average on March 1st
5. 140 % of average on April 1st

Table 4 provides a listing of the suspensions and the reason for suspension on this program for the 2003 through 2010 period.

5. PROGRAM OPERATIONS

NAWC's current weather modification permit, issued by the Colorado Water Conservation Board in 2007, authorized up to 28 manually operated ground based cloud seeding generators on this program. The actual numbers of generators in use has ranged from 20-25 per season. These generators are typically sited near the upwind slopes of the intended target areas. Sites are selected where local residents agree to the installation of a generator and propane tank on their property. Furthermore, these residents agree to operate these generators upon request from one of NAWC's meteorologists. Activation of the generators is relatively simple, consisting of opening a propane valve, then lighting the propane that exits into a burn chamber, and then adjusting the flow rate of the acetone-silver iodide solution which is sprayed into the propane flame. Deactivation consists of closing the flow rate meter, then closing the propane valve. Activation or deactivation typically takes five minutes or less. A photograph of one of these generators is provided in Figure 6.

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 analyses utilized include: weather satellite visual and infrared 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, and 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 material. The array of active generators is typically adjusted as the winds evolve with the passage of the storm through the target area. The project meteorologists who conduct the operations for this program work from NAWC's

Table 4. Seeding Suspensions, 2003-2010.

Dates of Suspension	Reason for Suspension	Parts of Target Area Impacted by Suspension
Jan. 2-4, 2004	Avalanche Warning	Entire Target Area
Jan. 9-11, 2005	Avalanche Warning	Southern Target Area
Dec. 19-20, 2006	Avalanche Warning	Southern Target Area
Dec. 7-8, 2007	Avalanche Warning	Northern Target Area
Jan. 6-7, 2008	Avalanche Warning	Entire Target Area
Jan. 27-28, 2008	Avalanche Warning	Entire Target Area
Feb. 3-4, 2008	Avalanche Warning, Excess Snowpack	Entire Target Area
Feb. 7-8, 2008	Excess Snowpack	Northern Target Area
Feb. 24-25, 2008	Excess Snowpack	Northern Target Area
Feb. 27- Apr. 15, 2008	Excess Snow pack	Entire Target Area
Dec. 23, 2008	Avalanche Warning	Western Target Area

main office located in Sandy, Utah or from their homes during non-business hours. A local part-time technician installs and maintains the silver iodide generators.

The number of seeded storm systems ranged from 13-22 per season. The corresponding number of generator hours ranged from 1473 to 4231 hours. Table 5 provides these data by individual seasons.

Some atmospheric scientists have questioned whether silver iodide particles released from valley locations in wintertime seeding programs become trapped by low-level temperature inversions

Figure 6: Manually Operated Silver Iodide Cloud Seeding Generator.

rendering the seeding ineffective. NAWC certainly agrees that valley inversions can trap silver iodide particles below them. The relevant question is whether such inversions are prevalent when

Table 5. Number of Seeded Storms and Total Generator Hours by Season

Seeded Season	Number of Storms	Generator Hours
2003-2004	20	3299
2004-2005	19	3416
2005-2006	18	4231
2006-2007	13	3297
2007-2008	14*	1473*
2008-2009	22	2868
2009-2010	19	2919

** Seeding Operations Terminated on Feb. 27th for rest of season*

seedable conditions exist over the intended target area. The basic question is “do inversions occur when there is supercooled liquid water over or upwind of the target barrier at temperatures treatable by silver iodide seeding?” NAWC performed an analysis of data obtained from two ground-based icing rate meters located at exposed sites on two different mountain barriers in Utah (Yorty et al., 2010). These data were collected during the 2009-2010 winter season. Meteorological conditions of interest in cloud seeding applications were examined during the occurrence of icing recorded by these devices. One such analysis considered low-level stability associated with the icing events at one of the sites (Skyline) located on a mountain crest on the Wasatch Plateau east of Fairview, Utah. Fairview sits in a significant mountain valley, the Sanpete Valley, which lies between the San Pitch Mountain Range to the west and the Wasatch Plateau to the east. An earlier research program conducted in this area (Super, 1999) had indicated that inversions were often present in the wintertime in this valley, but it is important to note that this analysis included soundings taken in pre-storm conditions. NAWC’s analysis, however, indicated that when the 700 mb temperature during icing periods at the Skyline site was between –5 and -15^{0} C that approximately 79% of these icing events occurred with a generally well-mixed atmosphere to the valley floor.

The Gunnison Valley is similar to the Sanpete Valley in Utah. Surface temperatures are frequently in the sub-zero (Fahrenheit) range in the wintertime under clear skies in the Gunnison Valley. Atmospheric inversions are common under these conditions as inferred from 700 mb temperatures compared to surface temperatures. It is likely these inversions often mix out during storm passages in a similar fashion to what happens in the Sanpete Valley in Utah. As a test of this hypothesis, NAWC ran a NOAA HYSPLIT trajectory model simulation for what would be considered a typical storm period in this area from the 2009-2010 winter season. This consisted of a 4-hour simulation from 00-04Z on Feb. 20, 2010. This simulation was for a ground release just west of Gunnison. Figure 7 provides a plan-view plot from the simulation. The model simulation indicates transport from the valley floor over the high mountain barrier to the east of Gunnison. This simulation indicates that the plume remained < 1000m above ground level as it passed over the barrier crest. Seeding from locations within the Gunnison Valley presents a rather unique situation in that the intended target area surrounds this valley on three sides. As long as the ground plumes pass over these higher elevation areas it becomes a situation of “you can’t miss” having seeding plumes pass over some part of the target area.

6. ESTIMATED INCREASES IN PRECIPITATION

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 focused on seeding every potentially seedable event. Thus, operational program sponsors are typically unwilling to employ some form of randomization of seeding decisions, a technique which could assist in evaluating the effects of seeding. Essentially these sponsors have sufficiently high confidence that cloud seeding can produce positive effects to warrant moving ahead with a non-randomized 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 following quote from a recently adopted American Meteorological Society Statement (AMS, November 2010) on Planned Weather Modification through Cloud Seeding addresses this issue; "It should be noted, though, that in practice large potential benefits can warrant relatively small investments to conduct operational cloud seeding despite some uncertainty in the outcome."

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

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

1. Statistical Approaches
2. Physical Approaches
   (e.g., silver in snow analyses)
3. Modeling Approaches

Research programs can be evaluated in a more rigorous fashion than operational programs since some type of randomization is applied, resulting in separate seeded and non-seeded data sets for comparison. The UGRB program is operational by design so other less rigorous evaluation techniques need to be considered.

6.1 Target/Control Regression Technique Applied to the UGRB Program

One commonly employed statistical technique used in evaluating operational programs 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., precipitation or streamflow). Records of the variable to be tested are acquired for an historical (not seeded) period of many years duration as possible (20 years or more are preferable). 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

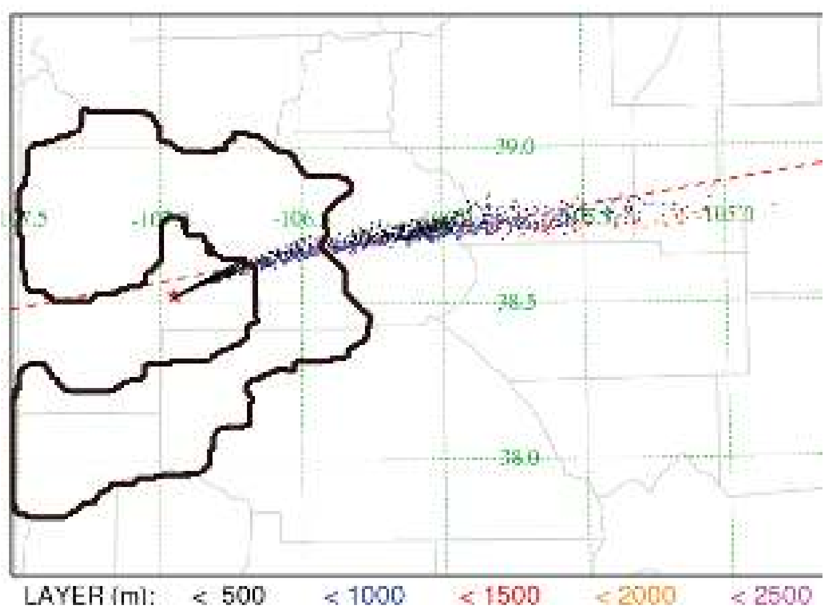

Figure 7: HYSPLIT Trajectory Simulation of a Four Hour Ground Release (color coding indicates height of plume above ground level).

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 or streamflow, based on precipitation or streamflow observed in the control area. This regression equation is then applied to the seeded periods to estimate what the target area precipitation or streamflow 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 or streamflow 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 areas. Generally, higher correlations are found where the target and control areas are similar in terms of elevation and topography. Control sites that are geographically 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 or streamflow 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 response variable (expected precipitation or snowpack) in the seeded years. An equation indicating perfect correlation would have an r value of 1.0.

It should be understood that the measurement of precipitation in mountainous areas is extremely difficult for a variety of well-documented reasons (e.g. gage bridging due to snow, wind causing reductions in gage catch, and wind causing drifting that may impact snow pillows). Some of the uncertainty in these evaluations is reduced since the same measurement techniques are being used in both the target and control locations and target and control are located at similar elevations, but the basic values of the amounts of precipitation and snow water contents in mountainous areas can be only considered approximations of the true values.

NAWC has routinely used this historical target/control approach in estimating the effects of its operational winter cloud seeding programs. The following discuss the application of this technique to the UGRB program.

NAWC typically selects potential target and control sites close to the inception of each operational program. Data were obtained from possible target and control stations. Some quality control procedures were then employed to determine whether some sites should be dropped from consideration due to missing data or relocation of stations, factors causing changes in the observations. Control sites were selected to avoid including sites that may have been impacted either historically or currently by other cloud seeding programs. For example, there are long-term, on-going seeding programs over the Grand Mesa and San Juan Mountains that were excluded from consideration.

April 1st snow water content data were obtained from the NRCS. Control and target area sites were initially selected after the 2002-2003 winter season, then modified for the 2003-2004 winter season to include additional target sites that were located within the expanded target areas. NAWC used the adjusted values calculated by the NRCS to account for the NRCS change over from the manual snow course data collection method to the automated SNOTEL data collection technique. Conversion to the SNOTEL technology began in Colorado in the early to mid 1980's. Average values for each winter season were determined from the historical snowpack data. The historical water years of 1971-76, 1978, 1983-84, 1986-92, and 1997-2000 were used, a total of 20 seasons. These seasons were selected to eliminate some historical seasons in which seeding from other seeding programs may have impacted the target area. A total of nine target area snow water content observation sites were selected. Six sites were selected as controls, based on obtaining high correlations with the target sites. The locations of these sites are provided in Tables 6 and 7. The target and control sites have remained the same since the 2003-2004 winter season. This factor renders these estimations as *a priori* in nature.

Linear and multiple linear regression equations were developed for the snowpack analyses. Elevations for the control area sites averaged ~9200 feet MSL, while those in the target area averaged ~9800 feet, adequately similar for the statistical comparisons. The simple linear regression equation developed relating the average control snowpack data and the average target snowpack data for April 1st water content for all target sites, was the following:

$$Yc = 0.75 * Xo + 1.67$$

where Yc is the calculated average April 1st snow water content (inches) for the 9-station target, and

Table 6. Snow Water Equivalent Control Sites					
Site No.	Site Name	Site ID	Elev. (ft)	Lat (N)	Lon (W)
A	Rabbit Ears	06J09	9,400	40º22'	106º44'
B	Crosho	07J04	9,100	40º10'	107º03'
C	Lynx Pass	06J06	8,880	40º05'	106º40'
D	Burro Mtn	07K02	9,400	39º53'	107º36'
E	LaSal Mtn, UT	09L03	9,850	38º29'	109º16'
F	Chamita, NM	06N03	8,400	36º57'	106º39'

Table 7. Snow Water Equivalent Target Sites					
Site No.	Site Name	Site ID	Elev. (ft)	Lat (N)	Lon (W)
1	McClure Pass	07K09	9,500	39º08'	107º17'
2	North Lost Trail	07K01	9,200	39º04'	107º09'
3	Butte	06L11	10,160	38º54'	106º57'
4	Park Cone	06L02	9,600	38º49'	106º35'
5	Porphyry Creek	06L03	10,760	38º29'	106º20'
6	Keystone	07L04	9,960	38º52'	107º02'
7	Crested Butte	07L01	8,920	38º53'	107º00'
8	Lake City	07M08	10,160	37º59'	107º15'
9	Cochetopa Pass	06L06	10,000	38º10'	106º36'

Xo is the 6-station control average observed April 1st snow water content. The r-value for this equation was 0.86, suggesting that 74% of the target/control variation is explained by the regression equation.

A multiple linear regression equation was also developed using the same data. The primary difference between the two mathematical methods is that, with the multiple regressions, the data from each control site is related independently with the target area average values. This normally allows a higher correlation (r-value) to be obtained. The equation developed for the multiple linear regression technique is as follows:

$$Yc = 0.08*X_1 + 0.51*X_2 + 0.34*X_3 - 0.50*X_4 - 0.03*X_5 + 0.23 * X_6 + 3.01$$

Yc is the 9-station target area average where X_1 is Rabbit Ears SNOTEL, X_2 is Crosho, X_3 is Burro Mountain, X_4 is Lynx Pass, X_5 is LaSal Mountain (Utah), and X_6 is Chamita (New Mexico). The r-value for equation (2) is 0.89, suggesting that 79% of the target/control variation is explained by the equation.

6.2 Results

April 1st snow water content data from the six control sites were averaged for each of the seven seeded seasons and then inserted into the linear and multi-linear regression equations, described in the previous section to predict the expected average April 1st snow water contents based upon the average of the nine target sites. The results are provided in Tables 8 and 9. In these tables, the predicted target averages were then compared to the observed target averages.

When the evaluation results of the seven full seeded seasons are combined, the average indicated increases range from 16% to 20% (for single and multiple regressions, respectively) for April 1 snowpack (Tables 8 and 9). Even these seven-season combined results may be skewed by natural variability in snowpack accumulation, and thus these numbers may be imprecise. For example, the 1.43 and 1.47 ratios (for the linear and multi-linear evaluations) for water year 2008 are unrealistically high which has the effect of raising the 7-year average values. If this high season is excluded, the six-season average becomes 10% and 14% respectively from the linear and multiple regression equations. It is concluded from these evaluations as well as those of similar programs in the mountainous west that an average seeding increase in the often-stated range of 5-15%, and possibly higher, may have resulted from this seeding program. The 5%-15%

range is one that is stated in a Weather Modification Association Capability Statement (WMA, 2005) as the likely range of seeding effects from winter programs. The results provided in Tables 8 and 9 should be considered preliminary indications.

Silverman, 2007, in an evaluation of a long-term winter seeding program in the Sierra Nevada states: "Assuming that the regression relationship derived from the historical period is representative of the operational period, the historical regression method may yield reasonably precise estimates of a multi-year effect of seeding provided that the natural variability is averaged over a sufficiently long period of years." NAWC agrees with this statement. We normally indicate to our clients that 10 to 15 seasons of seeding are typically needed for the indicated results from operational cloud seeding programs to stabilize. Therefore, this assessment of the Upper Gunnison River Basin program should be considered preliminary since there have been only seven seeded seasons to date.

Table 8. Summary of Seeded Seasons Evaluations using April 1 Snowpack Data, Based on Simple Linear Regression Equation.

Water Year	Control Average	Target Average	Predicted Target Snow Water Content	Observed/ Predicted Ratio	Observed Minus Predicted Precip.
2003*	13.8	NA	12.1	NA	NA
2004	8.3	9.0	7.9	1.14	1.1
2005	15.2	16.4	13.1	1.25	3.3
2006	16.6	13.7	14.2	0.96	-0.5
2007	9.2	9.3	8.6	1.08	0.7
2008	17.1	20.8	14.6	1.43	6.2
2009	15.2	14.4	13.1	1.10	1.35
2010	12.9	12.1	11.4	1.07	0.79
Mean	13.5	13.7	11.8	1.16	1.8

* 2003 snowpack analysis not used since seeding was only conducted during February and March

Table 9. Summary of Seeded Seasons Evaluations using April 1 Snowpack Data, Based on Multiple Linear Regression Equation

Water Year	X1	X2	X3	X4	X5	X6	Target Average	Predicted Target Snow Water Content	Observed/ Predicted Ratio	Observed Minus Predicted Precip
2003*	25.3	14.8	14.1	10.8	10.5	7.2	NA	NA	NA	NA
2004	20.7	6.8	10.2	6.8	4.4	0.6	9.0	8.2	1.10	0.8
2005	21.8	9.5	15.0	10.6	19.1	15.3	16.4	12.3	1.33	4.1
2006	35.5	16.1	18.0	14.2	11.7	4.2	13.7	13.7	1.00	0.0
2007	21.4	7.0	11.0	10.7	4.3	0.9	9.3	6.7	1.38	2.5
2008	32.0	15.4	16.6	14.9	11.2	12.7	20.8	14.2	1.47	6.6
2009	30.4	14.5	15.9	13.6	9.9	6.6	14.4	12.6	1.14	1.8
2010	14.7	9.6	13.9	8.6	17.0	13.3	12.1	12.0	1.01	0.1
Mean	25.2	11.3	14.4	11.3	11.1	7.7	13.7	11.4	1.20	2.3

* 2003 snowpack analysis not included since seeding was only conducted during February and March

NAWC typically does not report statistical significance levels for any indicated results obtained from evaluating operational cloud seeding programs. The primary reason for this position is due to the non-randomized nature of these programs. More discussion on this matter is provided in Griffith, et al., 2010.

7. ESTIMATED INCREASES IN STREAMFLOW

NAWC obtained streamflow data from a Bureau of Reclamation web site. That web site provided calculated inflows to Blue Mesa Reservoir on a daily basis. Calculated inflows were acquired for the historical water years of 1971-2000, a period before any seeding in the Upper Gunnison River area, although seeding operations had been conducted in surrounding areas (e.g., Grand Mesa, San Juan Mountains) for portions of this period. These data were converted into estimated **April through July** runoff amounts. The target area April 1 snowpack data (for sites used in the regular snowpack seeding evaluation) were used to establish snowpack/streamflow relationships. NAWC used both the linear and multiple linear regression techniques to obtain estimated streamflow increases corresponding to snowpack increases of 10% and 15%. These increases were applied to an "average April - July" period based on the regression period, which includes 30 seasons (1971-2000).

The linear regression technique showed only fairly good correlation with the target area snowpack sites, with an r^2 value of 0.67. The multiple linear regression had a much better correlation with an r^2 value of 0.82, meaning that some of the target sites were much better correlated with the calculated Blue Mesa inflow than others. Results are provided in Tables 10 and 11. The results of the linear evaluation suggest April – July streamflow increases of 11.7% (79,602 AF) and 17.5% (119,403 AF), based on the indicated snowpack increases of 10% and 15%, respectively. The multiple linear evaluation suggested higher increases of 14.1% (96,218 AF) and 21.1% (144,327 AF), for 10% and 15% snowpack increases, respectively.

Some may ask how higher percentage increases in runoff than in snow water contents can occur. We have found this to be a rather common outcome of such analyses. Perhaps one way to consider this is the fact that there will be a certain amount of water required from the snowpack to recharge the upper soil mantle before there can be any runoff. Once this requirement is met, the efficiency of conversion of snow water content to surface runoff (the basin efficiency) is much higher.

To determine how estimated increases in streamflow might fluctuate depending upon whether a given season was below or above normal, we looked at the analysis for the inflow to Blue Mesa and then used the regression equations to estimate the additional **April through July** streamflow in a 75% of normal and a 125% of normal winter season based upon target area April 1st snow water contents. We again applied the assumed 10% and 15% increases in snow water content to these below and above normal seasons. Tables 10 and 11 contain these results.

The results from 10% and 15% increases in the 75% of normal season were estimated increases of 12.3% (59,702 acre feet) and 18.5% (89,552 acre feet), respectively, using the linear regression equation. Likewise, the results from 10% and 15% increases in the 75% of normal season were estimated increases of 16.3% (72,163 acre feet) and 24.5% (108,235 acre feet), respectively, using the multiple linear regression equation.

Information for the 125% of normal season with 10% and 15% increases in April – July streamflow resulted in estimated increases of 11.3% (99,502 acre feet) and 16.9% (149,254 acre feet), respectively, using the linear regression equation. Likewise, the results from 10% and 15% increases in the 125% of normal season were estimated increases of 13.0% (120,272 acre feet) and 19.5% (180,409 acre feet), respectively, using the multiple linear regression equation.

The indicated increases in streamflow from Tables 10 and 11 fall within the range of indicated increases in streamflow from a separate analysis of a long-term winter cloud seeding program conducted for the Vail Ski area (Silverman, 2009) located in central Colorado. Indicated increases in this analysis ranged from 4.6 to 28.8% for several small drainage areas. Griffith et al., 2010 comments on Silverman's Vail analysis indicated an average increase of 8.4% when these drainages were combined. Again, these indicated increases in streamflow should be considered preliminary for the same reasons stated concerning the indicated increases in snow water content; only eight seeded seasons to date.

8. SUMMARY

The indications of seeding effectiveness from the target/control analysis technique when applied to April 1st snow water content suggest average increases for the seven seeded seasons of 16% (simple) and 20% (multiple) linear regression techniques. We believe that the very high positive indications from the 2007-2008 season are unrealistic due to that season's abnormal precipitation patterns and the manner in which these patterns impacted the control and target sites. This factor has the impact of inflating the seven-year averages. If that season were removed, the results from the six seeded seasons would be indications of increases of 10% from the linear regression and 14% from the multiple linear regression equations. These

Table 10. Estimated Increases of April – July Streamflow Into Blue Mesa Reservoir, Based on Linear Regression Equation

Estimated Increases	75% of Average Winter season	**Average Winter Season**	125% of Average Winter Season
% Increase in Streamflow with 10% increase in Snow water	12.3%	**11.7%**	11.3%
% Increase in Streamflow with 15% increase in Snow water	18.5%	**17.5%**	16.9%
Increase in Streamflow (acre feet) with 10% increase in Snow water	59,702 ac ft	**79,602 ac ft**	99,502 ac ft
Increase in Streamflow (acre feet) with 15% increase in Snow water	89,552 ac ft	**119,403 ac ft**	149,254 ac ft

Table 11. Estimated Increases of April – July Streamflow Into Blue Mesa Reservoir, Based on Multiple Linear Regression Equation

Estimated Increases	75% of average Winter season	**Average Winter Season**	125% of Average Winter Season
% Increase in Streamflow with 10% increase in Snow water	16.3%	**14.1%**	13.0%
% Increase in Streamflow with 15% increase in Snow water	24.5%	**21.1%**	19.5%
Increase in Streamflow (acre feet) with 10% increase in Snow water	72,163 ac ft.	**96,218 ac ft**	120,272 ac ft
Increase in Streamflow (acre feet) with 15% increase in Snow water	108,235 ac ft	**144,327 ac ft**	180,409 ac ft

percentages are in line with the 5-15% range contained in a Weather Modification Association Capability Statement (WMA 2005) as the likely range of seeding effects from winter cloud seeding programs.

Calculations were made of potential increases in April through July streamflow based upon the indicated increases in April 1st snow water contents. Increases in the range of 79,600 to 96,200 acre-feet in an average runoff season were indicated based upon a 10% increase in April 1st snow water content for an average winter season. Using an average cost of approximately $90,000 to conduct the program results in estimates of $0.94 to $1.13 per acre-foot of augmented runoff into Blue Mesa Reservoir.

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