UPDATE ON A LONG-TERM WINTER OPERATIONAL CLOUD SEEDING PROGRAM IN CENTRAL/ SOUTHERN UTAH

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ABSTRACT

North American Weather Consultants, Inc. (NAWC) has conducted operational winter cloud seeding programs in the mountainous areas of Central/Southern Utah since 1974. Beginning in 1988, seeding has also been conducted in three additional mountainous target areas within the State. The goal of these programs has been to enhance winter snowpack accumulation in the target areas, which now include most of the mountainous areas of the State. Studies have demonstrated that a large majority of the annual runoff in Utah streams and rivers is derived from melting snowpack, which explains the focus on wintertime seeding (within the November – April period). 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 (UDWR) and the three Lower Colorado River Basin States of Arizona, California, and Nevada, since 2007. An earlier NAWC WMA paper provided a summary of seeding operations for the water years of 1974 through 2007 for the four target areas. This paper is focused on the Central/ Southern Utah program which is both the largest target area and the longest running program in the State. It covers all but four water years from 1974 through 2021 and is one of the three or four longest operational winter cloud seeding programs that have been conducted in the United States.

The target area encompasses several mountain ranges in Central/ Southern Utah. NAWC has defined the target area boundaries as those locations that are above 7,000 feet MSL. This is a large area of approximately 10,000 square miles.

Cloud seeding is accomplished using networks of ground-based, manually operated silver iodide nuclei 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 and the Weather Modification Association.

NAWC historical target and control evaluations of this program indicate an average increase in December – March target area precipitation of 12% or an average increase in precipitation of 1.3 inches. These results were significant at the 0.06 level from a one-tailed Student's t-test. The UDWR has conducted periodic studies to estimate the increases in annual streamflow resulting from the estimated increases in April 1st snow water content produced by this seeding program. The most recent study (2018) indicated an estimated average annual streamflow increase of 83,654 acre-feet for the Central/Southern Utah target area. Factoring in the cost of conducting this program resulted in an estimate of the average cost of the augmented runoff to be $2.02 per acre-foot.

1.0 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 (NAWC) was contracted by a group of Central and Southern Utah Counties to initiate a winter cloud seeding program in the mountainous areas of central and southern Utah (Griffith et al. 2009). This program began in the 1973-1974 winter season and continued in the 1974-1975 winter season. The initial impetus to initiate this program was drought conditions that impacted southern Utah during the 1972-1973 winter season. The participating counties provided funding for the program. The Utah legislature passed a comprehensive weather modification law in 1973 (73-15-3 through 8). This legislation authorized the UDWR to both regulate and develop cloud seeding programs within the State. The UDWR began cost sharing with the local supporters of the Central/Southern cloud seeding program during the 1975-1976 winter season. That cost sharing program has continued to the present except for a break from 1984-1987, which was an extremely wet period throughout the State of Utah. Figure 1 provides a map of the Central/Southern Utah target area. It encompasses the mountainous areas above 7,000 feet MSL with an estimated area of 10,000 square miles. The locations of the 70 ground-based, manually operated silver iodide generators installed for the 2020-2021 winter season program, are included in Figure 1.

Fig. 1. Central/Southern Utah cloud seeding generator locations (red dots) used in the 2020-2021 winter season program. Target areas outlined in black.

2.0 ORGANIZATION

The cloud seeding program is supported at the county or multi-county level. A non-profit group, the Utah Water Resources Development Corporation, was organized in the 1950's to represent several 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 these programs have received cost sharing support since 1976 from the Utah Division of Water Resources. The typical portion of the costs funded by the UDWR in recent years has averaged 50% of the total program costs. Figure 2 provides the yearly cost sharing percentages for all of the Utah operational cloud seeding programs. There have been four separate seeding programs in Utah since 1988. Prior to that, the Central/Southern program was the only one active, which dated back to 1974. The three Lower Colorado River Basin States (Arizona, California and Nevada) provided supplemental funding support to the Central/Southern program beginning in the 2007 Water Year (October – September) and continuing through the 2021 Water Year. These states provided funding to extend the operational period from November 1st –

15th and March 15th – April 15th to impact those parts of this program's target area that could potentially provide additional runoff into Lake Powell and Lake Mead. Typically, this program was operated for five months from November 15th – April 15th each winter season through the 2006 Water Year. Beginning in Water Year 2007 the operational program was reduced to a four-month operational period November 15th – March 15th. This change coincided with the Lower Basin States funding that provided for seeding over a substantial part of the Central/Southern target area for the March 15th – April 15th period.

3.0 SCIENTIFIC BASIS

The Utah programs were originally designed based upon results obtained from research-oriented weather modification programs conducted in the western United States in the 1960's through the 1980's (e.g., Climax I and II, Mielke et al. 1981), the Colorado River Basin Pilot Project (Elliott et al. 1978), and the Bridger Range Experiment (Super and Heimbach 1983). 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 from 1981-1986 and the Wasatch Plateau located in central Utah from 1990-1998 (Super 1999). A recent winter cloud seeding research program has been conducted in southwestern Idaho known as the Seeded and Natural Orographic Wintertime Clouds (SNOWIE). This program was conducted during the 2016-2017 winter season. Sophisticated observational tools were deployed to observe winter clouds seeded by aircraft. These tools allowed for

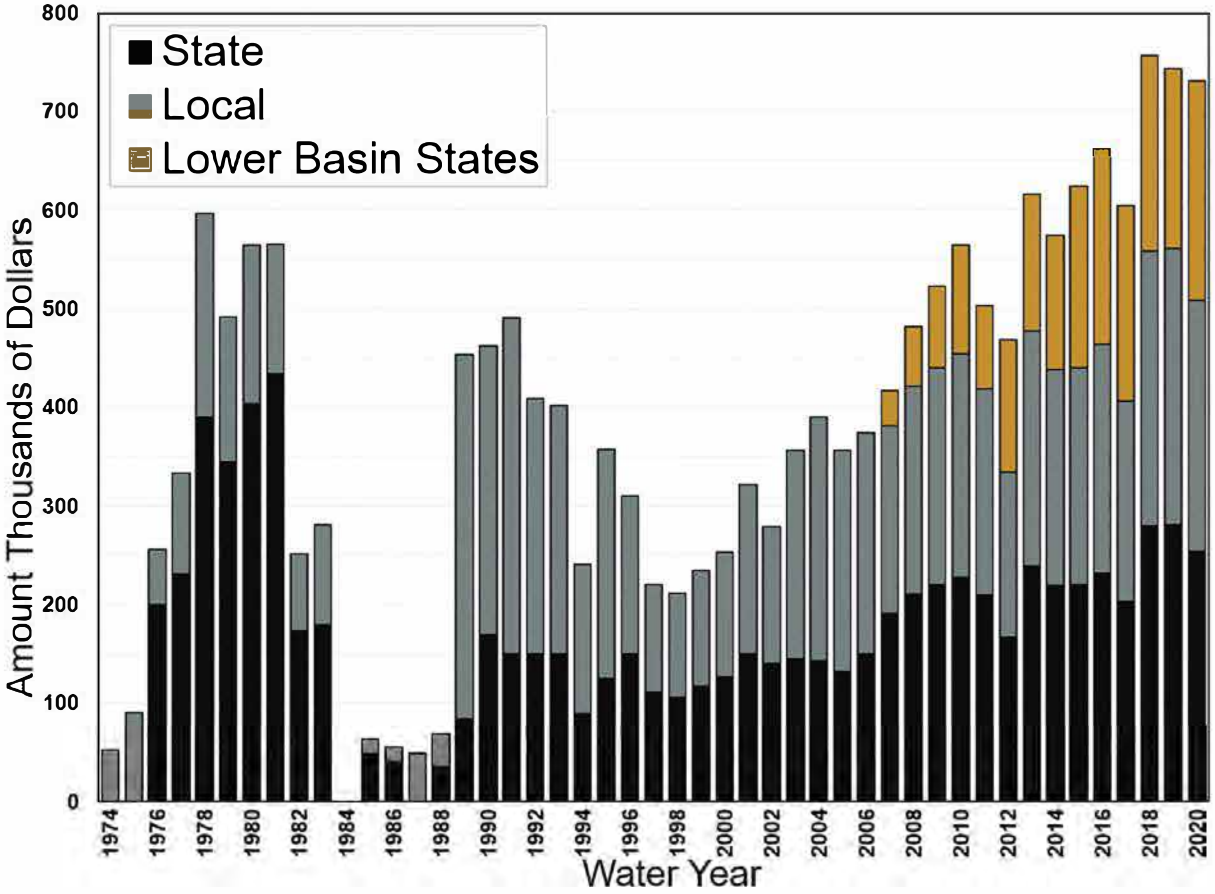

Fig. 2. State, Local and Lower Colorado River Basin States funding of Utah operational cloud seeding programs, 1974-2020.

the documentation of several links in the chain of events leading to increased precipitation reaching the ground (Tessendorf et al. 2019). This provided important verification of the hypothesized seeding chain of events from release of seeding material to augmented precipitation reaching the ground.

4.0 CONCEPTUAL MODEL

The basic conceptual model upon which the Central/Southern Utah seeding program is based can be summarized as follows:

Some of the naturally occurring winter storms that pass over Utah contain/produce supercooled cloud droplets. Supercooled means that droplets remain in liquid form at temperatures below freezing. Some of these droplets are not readily converted to ice crystals as they pass over the mountainous areas of Utah but can remain supercooled and subsequently evaporate instead. The presence of supercooled cloud droplets over the crests of these mountain barriers indicates that some 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, which are typically soil particles) that convert these supercooled cloud droplets into ice crystals. The deficit in natural ice nuclei occurs primarily in cloud temperatures in the 0 °C to -15 °C. Introduction of artificially generated silver iodide nuclei into cloud systems that contain supercooled cloud droplets in approximately the -5 °C to -15 °C range will artificially nucleate (freeze) some of these supercooled cloud droplets. The -5 °C temperature is considered the nucleation threshold of silver iodide, which is the seeding material that has been used for this program. 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, typically along with natural snowflakes, resulting in increases in precipitation above that which would have occurred naturally.

Previous Utah cloud seeding research programs have determined that supercooled cloud droplets frequently occur upwind and over Utah mountain barriers (e.g., Super 1999; Griffith et al. 2013). Figure 3 is a conceptual depiction of an orographically induced liquid water accumulation zone. In most winter Utah storms a portion to a significant portion of this zone would be below freezing, which means there would be supercooled cloud droplets present in this zone which can be affected by glaciogenic winter seeding programs. More recent deployment of microwave radiometers in Utah (Brian Head Ski area, Moab, and Roosevelt) have documented the presence of supercooled liquid water over or near Utah mountain barriers in the November – April period (e.g., Beall et al. 2018). Research in a variety of locations has indicated that background concentrations of natural ice nuclei are low in the warmer portions of the atmosphere but increase exponentially at colder temperatures. Prior research conducted in cloud chambers has demonstrated the

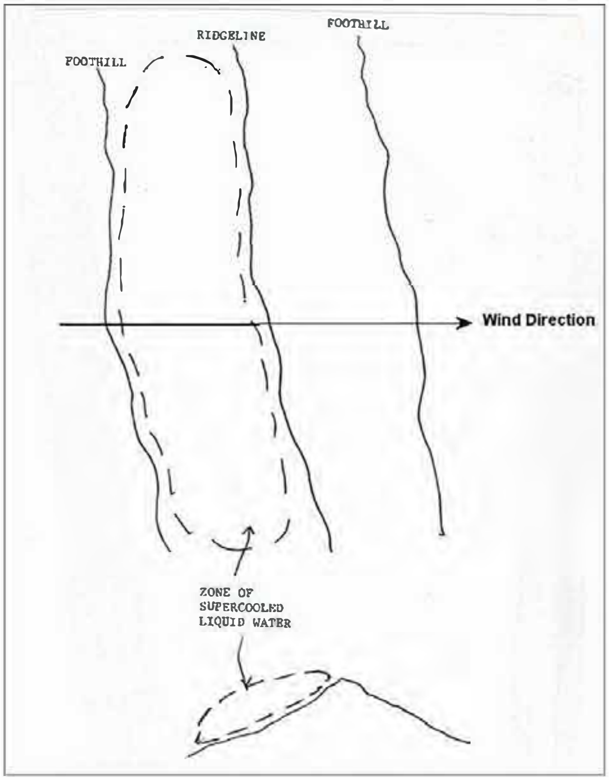

Fig. 3. Conceptual depiction of an orographically induced liquid water accumulation zone; horizontal and vertical depictions.

ability of silver iodide nuclei to serve as freezing nuclei in significant concentrations beginning near the -5 °C level and increasing exponentially to the -20 °C to -25 °C level (Garvey 1975; Finnegan 1999). Based upon an analysis of data from some ground-based icing meter sites in Utah (funded by the Lower Colorado River Basin States), there was little supercooled liquid water present at temperatures < -15 °C (Griffith et al. 2013). Since the elevation of these sites was approximately 10,000 feet MSL, temperatures at 700 mb can be used to estimate the lower temperature limit in determining seedability of specific storms.

5.0 PROGRAM DESIGN

The program design is based upon the results obtained from previous research programs in which the results are believed to be transferable to Utah and implementation is based on methods that are compatible with the conceptual model. The Utah design is consistent with criteria established by the American Society of Civil Engineers (ASCE 2016). Seeding relies upon the use of manually operated, ground-based silver iodide generators, 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) that aircraft had to be flown based upon FAA approved routes, the seeding aircraft likely flying above the supercooled cloud droplet accumulation zone depicted in Figure 3, and the difficulty in effectively covering the large Utah target areas even with multiple aircraft. These factors resulted in limited seeding upwind of a given point on the ground when using aircraft during "seedable" (meeting established seeding criteria) situations.

5.1 Silver Iodide Nuclei Generators

The operational winter cloud seeding programs in Utah rely upon the release of silver iodide nuclei from strategically placed, manually operated ground-based ice nuclei generators located in valley or foothill locations (see Figure 1). Since winds that accompany winter storms in Utah typically flow in basically a west to east fashion (meteorologically referred to as winds having a westerly component), generators are placed in valley and foothill locations primarily on the western sides of the targeted mountain barriers. Such locations allow targeting of the supercooled cloud droplet accumulation zone depicted in Figure 3. Each generator is located at a residence or other accessible location. The resident or operator is trained on the operation of the generator and activates/terminates seeding upon instructions from one of NAWC's meteorologists. The current seeding solution contains a 2% 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 8 grams per hour. The 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 previously used solutions that produced pure silver iodide particles that act as contact nuclei. The addition of paradichlorobenzene results in a AgI(Cl)NaCl complex. The modified particles produced by combustion of the revised formulation act as ice nuclei much more quickly (probably through condensation-freezing nucleation) than contact nucleation. Figure 4 provides a photograph of one of these manually operated ground-based generators.

Several studies have been conducted concerning the potential environmental impacts of using silver iodide as a cloud seeding agent. The following is a quote from the Weather Modification Association's 2009 Environmental Position Statement (WMA 2009): "The published scientific literature clearly shows no environmentally harmful effects arising from cloud seeding with silver iodide aerosols have been observed; nor would they be expected to occur. Based on this work, the WMA finds that silver iodide is environmentally safe as it is currently being dispensed during cloud seeding programs". This statement includes several references that support this conclusion.

Fig. 4. Ground based, manually operated Silver Iodide nuclei generator.

Some would argue for higher elevation, remotely operated ground-based generators to be used on this Utah cloud seeding program. In a strictly technical sense this approach has merit, based primarily due to the concern that effluent released from lower elevation sites might become trapped by low-level atmospheric conditions (e.g., inversions) during seedable situations. There are several considerations important in this discussion: economics, feasibility, and observations.

NAWC had 70 manually operated ground generators installed for the 2020-2021 winter season in Utah for this Central/Southern cloud seeding program. Locations were provided in Figure 1 which also contains the outline of the target areas. The initial cost of remotely controlled ground generators is approximately $50,000 each without any consideration of installation or annual maintenance costs. A network of 70 remotely controlled generators that would match the number of NAWC's lower elevation generators would cost approximately $3,500,000. The fabrication of 70 manual generators would cost approximately $3,000 each for a total cost of $210,000. The American Society of Civil Engineer's Guidelines for Cloud Seeding to Augment Precipitation (ASCE, 2016) states for an augmentation program to be feasible it must be both technically and economically feasible. Previous NAWC feasibility studies of proposed winter cloud seeding programs in the Intermountain West have typically indicated that some 60-70% of the seedable situations could be seeded with a network of well-placed lower elevation, manually operated AgI generators (Griffith et al. 2010; Griffith et al. 2017). NAWC has often recommended that a core seeding program could be developed using this approach since calculations often indicated this would be the most cost-effective seeding approach. If there is interest in maximizing seeding increases, other seeding modes (e.g., remotely operated ground generators or seeding aircraft) could be considered. Each of these seeding modes are inherently more costly than the core program approach but can perhaps capture additional seeding potential not obtained with the core program approach. These other modes may be effective in perhaps an additional 30% of the seedable cases.

Following ASCE Guidelines, it then becomes a question of whether these other seeding modes are technically and economically feasible. Such modes may be considered technically feasible but not economically feasible due to the expected runoff from such seeding modes and the value of the augmented runoff. NAWC has often found that the design of a winter cloud seeding program can be closely tied to the value of the augmented precipitation (often snowpack-driven for winter orographic seeding programs). In other words, does the additional runoff produce a favorable benefit/cost ratio? Water in Utah for agricultural purpose is worth \$10-15 per acre-foot and \$50 to a few hundred dollars per acre-foot for municipal water supplies (Utah State Water Plan, 2001). Contrast these values with the value of municipal water in parts of California, which may be worth several hundred dollars to \$1000 or more per acre-foot. A NAWC feasibility study for San Luis Obispo County, California contained an estimate of the value of augmented streamflow to be \$1200 per-acre foot (Griffith et al. 2019). Consequently, more technically advanced seeding programs may be justified in California or other states where the value of augmented streamflow is high. The ASCE recommends at least an estimated benefit/cost ratio of 5/1 be maintained for a proposed program to be considered economically feasible.

There are other complications regarding the implementation of a large, remotely controlled generator network for the Central/Southern Utah program. 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 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 for three winter seasons (Super 1999). The critical missing information in this analysis was how often supercooled cloud droplets were occurring at seedable temperatures over the mountain barrier during these periods. The trapping of silver iodide nuclei under these conditions may have frequently been in pre-frontal conditions with little seeding potential. This supposition on NAWC's part receives strong support from this same Utah research program, which was based on an analysis of 100 hours of data from seven relatively wet storms in which supercooled liquid water was present. Several of NAWC's lower elevation generators were being operated during these periods, and 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. However, most hours with supercooled liquid water amounts of 0.05 mm or greater had weak embedded convection present, which likely assisted vertical silver iodide transport."

In recent years, the three Lower Colorado River Basin States have provided additional funding to support cloud seeding programs in Utah that may potentially provide augmented runoff to Lake Powell or Lake Mead. One form of augmentation has been the installation of high elevation ground-based icing meter sites. These sites can detect the presence of supercooled cloud droplets in passing winter storms. NAWC performed an analysis of some of these observations to consider the impact of low-elevation inversions possibly trapping lower elevation manually generated seeding plumes. This study concluded that such seeding would be effective in approximately 75% of the otherwise seedable situations studied in Utah (Yorty et al. 2012).

5.2 Generalized Seeding Criteria

NAWC has developed some generalized winter orographic cloud seeding criteria. These criteria were developed from previous research programs and field observations for use by its 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? Is some of this supercooled liquid water present at temperatures of -5 °C or colder?
2. Can some of the installed ground generators be used to effectively target this seeding potential?

Table 1 provides these generalized seeding criteria.

TABLE 1. Generalized Seeding Criteria

Cloud bases are below mountain barrier crest.
Low level wind directions and speeds would favor the movement of the silver iodide particles form the release points into the intended target area.
No low-level atmospheric inversions or stable layers that would restrict the vertical movement of the silver iodide particles form the surface to at least the -5 °C (23 °F) level or colder.
Temperature at mountain barrier crest height expected to be -5 °C (23 °F) or colder.
Temperatures at the 700 mb level (approximately 10,000 feet) expected to be warmer or equal to -15 °C (5 °F).

5.3 **Suspension Criteria**

Previously used cloud seeding suspension criteria used on the Utah winter cloud seeding programs have been updated by UDWR and the Utah Climate Center (Khatri et al. 2021) and reviewed by NAWC.

These criteria are primarily concerned with:

- Rain-induced winter floods.
- Excessive snowpack accumulations

The potential for wintertime flooding from rainfall on low elevation snowpack is high in some of the more southern Utah target areas during the late winter/early spring period. Every precaution must be taken to ensure 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 cloud seeding when any increase in precipitation has the potential of creating or adding to a flood hazard.

Prior to 2019, the following set of statewide threshold snow water equivalent (SWE) criteria, based upon observations from Natural Resources Conservation Service (NRCS) SNOTEL site observations, had been employed as a guide for possible suspension of operations.

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

Khatri et al. 2021 developed statistical methods to establish relationships between snow water equivalent (SWE) values and observed streamflow (here defined as critical flow). Critical flows represent the 95th percentile cumulative volume of the seasonal streamflow (April to July). SNOTEL data considered in this study were from sites located within the catchment of each river basin, have long historical observational data records available, and have been continuously updated by the NRCS. The calculated average suspension criteria in all cloud seeding target areas are 230%, 197%, 183%, and 178% for January 1st, February 1st, March 1st, and April 1st, respectively. Criteria for any date between two months can be interpolated from the monthly values. Unlike the existing practice of taking a single percentage value for the entire state, these methods use a project specific SWE value for each month which varies per basin. The results also suggest ranking the SNOTEL stations to be considered during the suspension decision.

Recognizing the complexity, variability, and uncertainties in the meteorological variables, cloud seeding processes, and watersheds, the final suspension decision should be made after a thorough assessment of other important factors including: (1) extreme weather conditions (warning of extreme storms, avalanche danger, local flooding, or potential flash flood warnings); (2) amount of precipitation in prior seasons, soil moisture conditions in the basin, reservoir storage level, and streamflow forecasts; and (3) potential increased risks of flooding due to wildfires.

6.0 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 infrared imagery, surface and upper-air analyses (especially those at the 700 mb level), rawinsonde skew-t plots, surface observations, video cameras, weather radar displays, 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 effects. Different generators may be operated as the winds evolve with the passage of the storm through the target area. An atmospheric dispersion model, Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT), developed by the National Oceanic and Atmospheric Administration, can be run in real-time by the project meteorologist to predict the transport of the seeding plumes. A ground-based, high elevation icing meter site has been operated at the Brian Head Ski area (southern Utah) for several winter seasons to support the Central/Southern Utah seeding program. Funding has been provided by the three Lower Colorado River Basin States. These devices provide real-time information to NAWC meteorologists regarding whether any supercooled liquid water is present and the associated wind speed/direction, precipitation, and temperature.

7.0 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 focused on seeding every potentially seedable event. Thus, operational program sponsors are typically unwilling to employ some form of randomization of seeding decisions, which could assist in evaluating the effects of seeding. Randomization of seeding decisions is a tool most often employed on cloud seeding research programs. Essentially these sponsors of operational programs 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 could be one of the primary goals in the conduct of a research program. This sentiment was expressed in a Bruintjes 1999 cloud seeding review paper, the following is a quote from this paper. "The fact that many operational programs have been on going and have increased in number in the past 10 years indicates the ever-increasing need for additional water resources in many parts of the world, including the United States. It also suggests that the level of proof needed by users, water managers, engineers, and operators for the application of this technology is generally lower than what is expected in the scientific community. The decision of whether to implement or continue an operational program becomes a matter of cost/benefit risk management and raises the question of what constitutes a successful precipitation enhancement program".

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 significance level attached to any indicated results is often required. Sponsors of operational programs are accustomed to dealing with much more uncertainty than this on almost a daily basis.

There are three basic types of evaluations that can be applied to operational cloud seeding programs:

- Physical evaluations, for example, measurements of silver content from seeded storms assuming silver iodide is the seeding agent.
- Modeling evaluations (e.g., use of computer models to predict the unseeded amounts of precipitation, snowfall, or streamflow).
- Target and control area evaluations.

NAWC has typically used a target and control evaluation technique in annual evaluations of its winter operational cloud seeding programs.

7.1 Target and Control Evaluations

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., precipitation, snow water content or streamflow). Records of the variable to be tested are acquired for an historical (not seeded) longest period available (20 years or more if possible). These records are partitioned into those located within the designated target area of the project and those in nearby upwind control areas. Ideally the control sites should be selected in areas meteorologically similar to the target, but 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 periods.

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 natural target area precipitation, based on precipitation observed in the control area. This regression equation is then applied to the seeded periods to estimate what the target area precipitation or snow water content 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 occurred during the seeded period, to determine if there are any differences potentially caused by the 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. 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 snow water content 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 (e.g., expected precipitation or snowpack) in the seeded years. An equation indicating a perfect correlation would have an r value of 1.0, a value never achieved in such analyses.

The measurement of precipitation in mountainous areas is extremely difficult for a variety of well-documented reasons (e.g., gauge bridging due to snow, wind causing reductions in gauge 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 typically being used in both the target and control locations and target and control sites are located at similar elevations, but the measured values of precipitation and snow water content in mountainous areas can be only considered approximations of the true values.

7.2 NAWC Central/Southern Utah Target and Control Evaluations

NAWC has used the target and control technique to evaluate its Central/Southern Utah cloud seeding program. Two types of data have typically been used in developing these equations relating target and control areas: 1) an accumulation of monthly precipitation data representative of the primary 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 Resources Conservation Service (NRCS, formerly the Soil Conservation Service).

NAWC has typically selected potential target and control sites close to the inception of each operational program. This is done to remove the question of bias; for example, this eliminates the potential to change the mix of target and control sites each season to derive a better outcome. In this sense these evaluations become a priori, not a posteriori analyses. For this program, data were obtained from possible target and control stations to develop the regression equations near the initial onset of seeding in 1974. Some quality control procedures were then employed to determine whether some sites should later be dropped from consideration due to missing data or relocation of stations, causing a change 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. Data were spatially averaged for the potential target and control sites and linear regression equations were developed from these data. The goal was to find the mix of possible control sites that provided the highest correlation with the target sites. The regression equations developed using these procedures were then used in subsequent seeded seasons without change except in two situations. First, if a station was discontinued, NAWC developed a new regression equation, which often consisted of the addition of just one alternate site to replace the location that had been discontinued. Second, NAWC recalculated all the April 1st snow water content equations in 2004 to utilize NRCS-estimated data that attempted to normalize data collected by two different means. Monthly manual snow course measurements were the norm before the advent of the NRCS SNOTEL program. SNOTEL site installations began in the west in the early 1980's. SNOTEL sites were typically established at prior snow course sites. Normally a ten-year overlap period using both types of observations was obtained. The NRCS then used this overlap period to provide estimates of what the prior monthly snow course data would have been had the SNOTEL measurements been available historically. NAWC compared target and control regression equation results using historical manual snow course observations versus the results when using the adjusted snow water equivalent (SWE) values. This analysis indicated a significant difference between the two evaluations. Based on this analysis, NAWC considered the evaluations using precipitation data more representative than the evaluations based upon the NRCS adjusted SWE data.

The Central/Southern Utah target area is represented by 25 precipitation gauge sites. A few of the target site gauges are NWS cooperative observer sites, but the large majority consist of SNOTEL storage gauges. These sites are shown in Figure 5. The sites are located throughout the target area and should provide a representative data set for the evaluation. The average elevation for the target gauge array is about 8,800 feet MSL. The precipitation evaluation control sites are located in eastern Nevada and north central Arizona (bracketing the target area on the northwest and southeast). Such locations are typically upwind of the target area during storm periods which avoids possible seeding contamination of the control sites. The locations of these sites are also shown in Figure 5. These sites have remained the same for a significant number of years, except for a few minor changes involving elimination or replacement of some valley co-op sites due to missing data or poor data quality. The historical period consisted of an 18-year period (1957-1973, and 1984). Seeded water years began

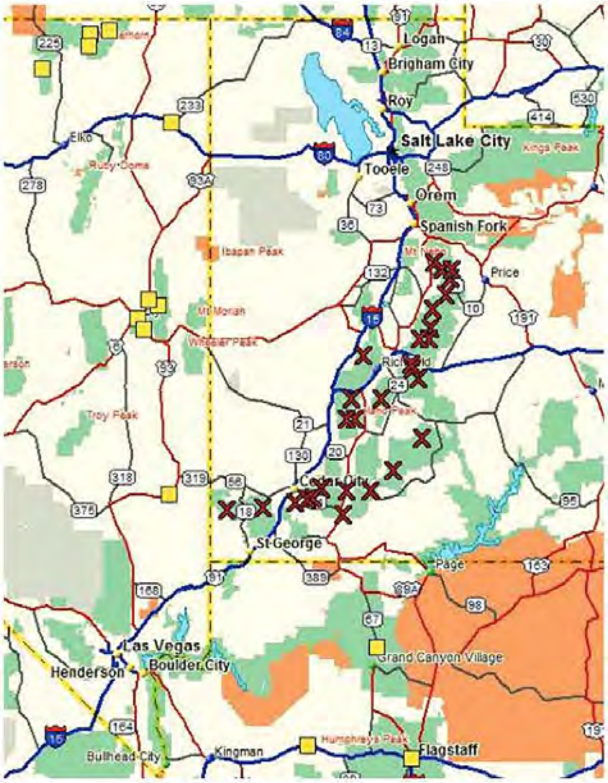

Fig. 5. Precipitation, target (X) and control (square) site locations used in the target and control evaluations.

in 1974 and continued through 1983. Although seeding resumed in the southern portion of the target area in 1985, it was not until 1988 that most of the target area was again being seeded. Therefore, the 1984-1987 period has been excluded from the evaluation, with target-wide seeding resuming in 1988 and continuing through the 2021 water year. This provides a total of 44 seeded seasons for evaluation.

The linear regression equation relating the target and control areas for this program is: $y = 1.69x - 3.17$ 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 value for this equation is 0.96, a very high correlation with an r^2 value (variance) of 0.91. This linear regression equation was used to predict the average natural target area precipitation for the seeded December – March periods. The observed average target area precipitation amounts were divided by the natural predictions from the regression equation. Values greater than 1.0 in this ratio would indicate more precipitation in the target area than that predicted from the control sites. Over the 44 seeded years included in the long-term seeded record, 12 percent more precipitation has been observed (on average) than would have been expected from the control area-based predictions. This has provided an estimated annual average excess of over 1.3 inches of water throughout the target area. Statistical tests show the long-term average to be very meaningful (i.e., not the result of chance), even though individual-year results are not statistically significant. A Student's t, one-tailed significance test for the predicted vs. observed values (all seeded seasons) yielded a P value of 0.06 for this evaluation. This suggests only a 6% probability of the positive results of this evaluation being due to chance. It should be noted that any potential seeding impacts that may have occurred during the November 15th – 30th period would not be included in this analysis since only monthly precipitation data were available dating back to 1957 when the original regression equation was developed.

Figure 6 is a scatterplot showing a comparison between the seeded (red dots) and non-seeded data (black dots) in the target area. The linear regression equation (e.g., best linear fit to the historical non-seeded data) is represented by the black diagonal line. Points above the line indicate seeded seasons in which there was indicated increases in precipitation. This analysis indicates that approximately 80% of the seeded seasons had more precipitation than that predicted by the regression equation.

A double mass plot is an engineering tool designed to display data in a visual format in which it can readily be seen if there has been a change in the relationship between two variables. NAWC has applied this technique to the Central/Southern Utah cloud seeding program's precipitation data. Figure 7 provides a plot of the above data sets. Target and control area-average seasonal values for both the historical (not-seeded) and the seeded periods are plotted on this figure. The December – March precipitation data are used in these plots since these data best represent the seeded seasons. The plotted values are cumulative; that is, each new season is added to the sum of all the previous seasons. In Figure 7, a line has been drawn through the points during the not-seeded base period. The plots show a stable relationship as evidenced by a consistent slope of the line drawn through these points. For comparison with the seeded period, the line describing the not-seeded period is extended at a constant slope through the seeded period. Figure 7 indicates a change in the relationship between the target and control areas (a sustained change in the slope of the line representing the seeded seasons) that begins a few years after the start of the cloud seeding programs in the mid to late 1970s. Note that when using the double mass plotting technique, it may take several data points to establish a trend. NAWC believes that this demonstrates evidence of a consistent positive seeding effect. A separate line could be drawn through the data points since seeding began in each case. Such a line would also have a fairly constant slope, departing from the slope of the line describing the not-seeded base period.

7.3 Downwind Seeding Effects

A recurring question regarding cloud seeding programs is whether the cloud seeding program is reducing precipitation downwind of the intended target area(s). This question is sometimes referred to as whether you are "Robbing Peter to pay Paul." NAWC has attempted to at least partially answer this question by analyzing precipitation downwind of the Central/Southern Utah winter cloud seeding program. Estimation of seeding effects on an area downwind of this target area were summarized in a 2003 study (Solak et al. 2003). The results of the original study have been updated through the 2018 water year (Yorty 2019). Seeded target area analyses of December – March high elevation (NRCS SNOTEL) precipitation data for this program indicate an overall season average increase

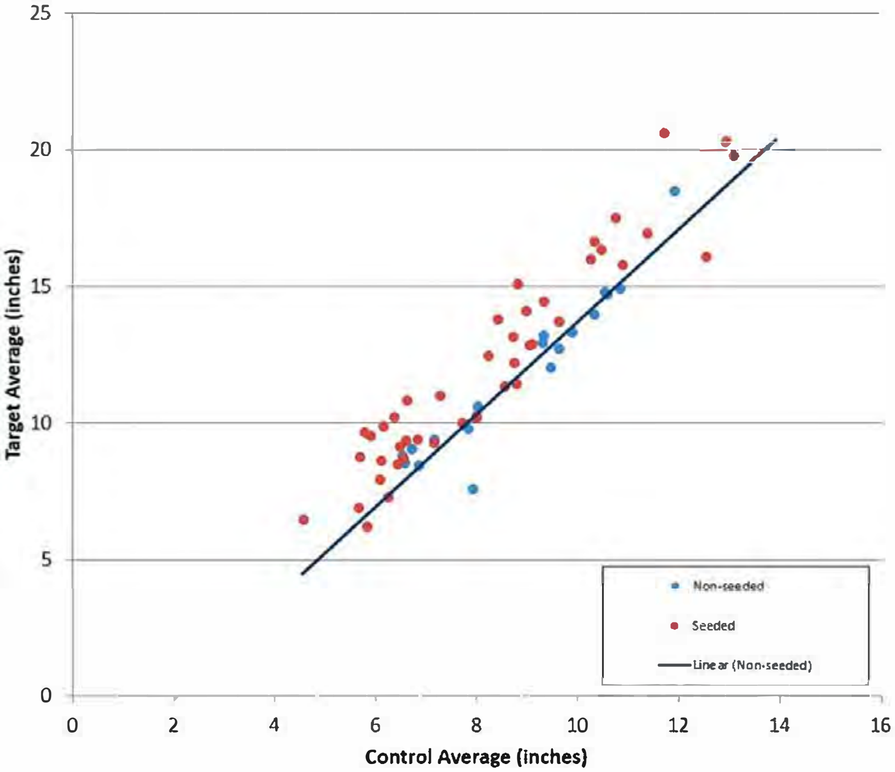

Fig. 6. Scatterplot of historical non-seeded (blue) vs seeded (red) data points for the December-March precipitation evaluation. The diagonal line represents the linear regression equation for the non-seeded period.

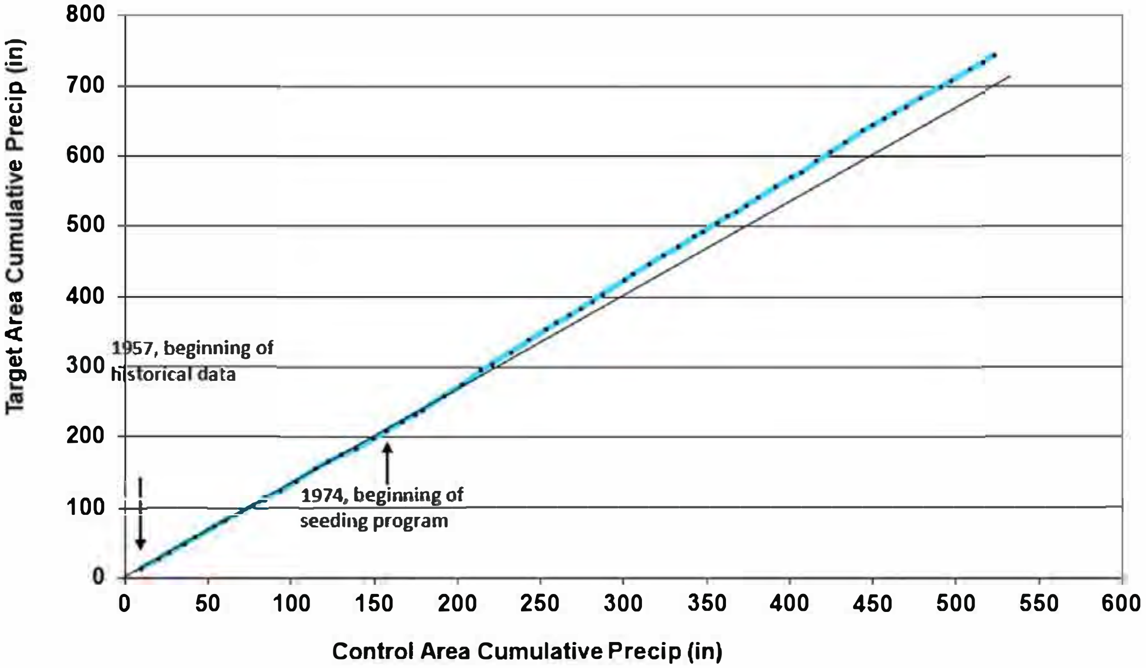

Fig. 7. Double mass plot of the accumulated target area versus control area precipitation with time from water years 1957 to 2021. The black line is drawn through the earlier not seeded years then extended into later years that depicts a deviation indicating more precipitation in the target area than predicted by a regression equation based upon a target and control evaluation.

of 12% for 41 seeded seasons. Estimations of downwind seeding effects were made for individual stations and various distance bands downwind. The analyses suggest downwind increases of similar percentages to those for the target at closer ranges to the target area with positive indications extending to approximately 100 miles downwind (approximately the Utah/Colorado border area). At approximately 100 miles downwind, the area-averaged ratio values (observed divided by predicted values) approach 1.0, suggesting a lack of any significant seeding effects at those distances. Expressed as average-depth precipitation amounts, the target area precipitation increase from seeding is estimated at 1.3" of additional water, with much lower precipitation increases in the much drier downwind areas within 100 miles, trending to 0 beyond this distance. There is also a paper on downwind seeding effects that considered several different target areas including the Central/ Southern Utah program (DeFelice et al. 2014. This paper indicated positive seeding effects downwind of the primary target areas in the range of 5% to 15% increases.

8.0 ESTIMATED INCREASES IN STREAMFLOW AND ESTIMATED COST OF AUGMENTED STREAMFLOW

Dr. Norman Stauffer of the Utah Division of Water Resources reported on some work he had conducted to estimate increases in streamflow that could result from 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:

- Estimate the average annual runoff from the areas that are being seeded (target areas).
- Estimate the increase in April 1st snow water content attributed to seeding.
- Determine the relationship (equations) between annual runoff and April 1st snow water content for major gauged rivers and streams in the target areas.
- 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. These areas included Western Box Elder County, Eastern Box Elder and Cache Counties, Eastern Tooele County, and Central/Southern Utah. This analysis estimated the average annual increase in streamflow from these four seeded areas to be 249,600 acre-feet. The resulting cost of producing the estimated additional water was $1.02 per acre-foot.

The UDWR periodically reviews the estimated streamflow increases in part by estimating the benefit by price per acre-foot augmented via cloud seeding by applying results of the NAWC target and control analysis performed annually. The estimated average annual increase in runoff in the Central/Southern program through 2015 was 83,654 acre-feet at a unit cost of $2.02 per acre-foot of water (Nay et al. 2018).

As a side note, the December – March precipitation evaluations do not estimate any possible effects of seeding which was conducted outside of the four-month core evaluation period. The Lower Colorado River Basin States funded extension periods of November 1st – 15th and March 15th – April 15th each winter season since 2007, targeting those portions of the Central/Southern target area that could contribute inflow to Lake Powell and Lake Mead. NAWC performed an analysis of the potential increases in streamflow from these extension periods at the request of a Lower Basin States representative. This analysis provided estimates of average March – July increases in streamflow to Lake Powell (20,271 acre-feet) and to Lake Mead (8,331 acre-feet). The estimated cost per acre-foot of the calculated average increases were $1.22 per acre-foot for inflow to Lake Powell and $1.81 per acre-foot for inflow to Lake Mead.

9.0 SUMMARY

A long-term, operational winter cloud seeding program has been conducted in Central and Southern Utah most winter seasons, beginning in 1974, to the present. This program has targeted several different mountain ranges with a lower elevation boundary of 7,000 feet MSL. It is estimated this target area encompasses approximately 10,000 square miles. This program is designed to increase higher elevation snowpacks, the goal being to enhance spring and summer runoff that benefits a variety of users. The cost of these programs has been shared between the State of Utah, Division of Water Resources, and local entities consisting of Counties or Water Conservancy Districts. The three Lower Basin Colorado River Basin States (Arizona, California and Nevada) have provided funding support to this program beginning in 2007. NAWC has been the Contractor that has conducted and evaluated this program.

The program design was originally based upon similar historical research programs conducted in Colorado and Montana and updated more recently based upon federally funded research programs conducted within this target area. Ground-based manually operated silver iodide nuclei generators have been the chosen cloud seeding mode. There were 70 such generators installed for this program during the 2020-2021 winter season. NAWC meteorologists determined when cloud seeding opportunities existed and instructed local generator operators when to turn on and turn off their generators. Previously established seeding suspension criteria were evaluated to determine whether seeding operations should be conducted at the beginning of each seedable storm or possibly terminated during a storm if conditions changed.

NAWC utilized an historical target and control regression analysis technique to estimate the effects of cloud seeding in this target area. Upwind control areas were located in Eastern Nevada and Northern Arizona. Precipitation data for the December-March period from a period without any seeding was used to develop a linear regression equation relating the two areas. A high r^2 value of 0.91 was obtained. This equation was used to predict the amount of natural precipitation during the seeded seasons. The observed precipitation amounts were divided by the estimated natural precipitation. An estimated average increase of 12% was indicated equivalent to an average 1.3 inch increase. These results were significant at the 0.06 level from a one-tailed Student's t-test. A plot of the seeded and not seeded seasons versus the linear regression equation line indicates that approximately 80% of the seeded seasons had more precipitation than that predicted by the regression equation.

The Utah Division of Water Resources periodically reviews the potential results from Utah cloud seeding programs by estimating the benefit by price per acre-foot of augmented streamflow via cloud seeding by applying results of the target and control analysis performed annually. The estimated average annual increase in runoff in the Central/ Southern project through 2015 was 83,654 acre-feet at a unit cost of $2.02 per acre-foot of water (Nay et al. 2018).

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