Annual Cloud Seeding Report

Southern & Central Utah Program
2020-2021 Winter Season

Prepared For:

State of Utah Division of Water Resources

Utah Water Resources Development Corporation

Lower Colorado River Basin States

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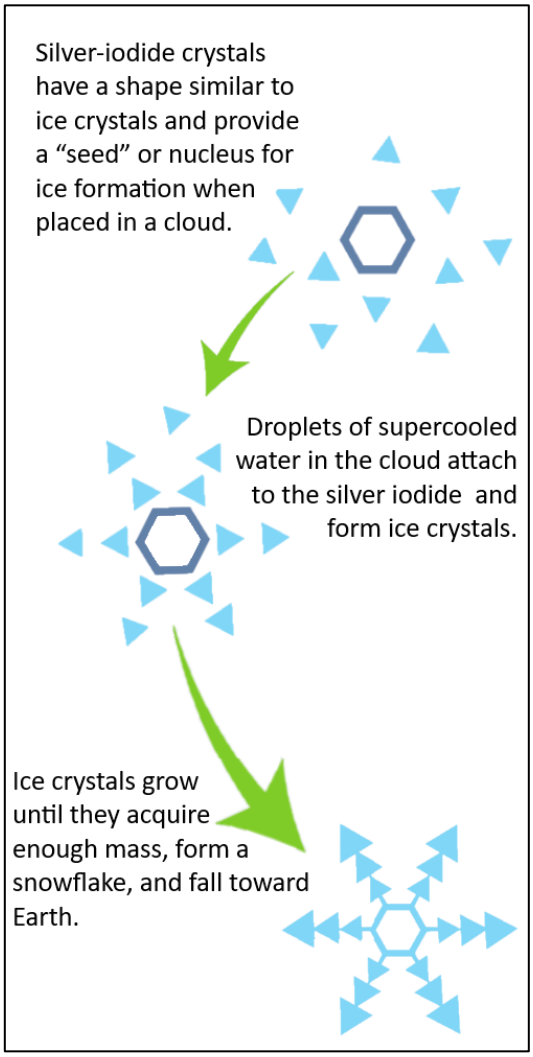
WEATHER MODIFICATION OVERVIEW

The Science

The cloud-seeding process aids precipitation formation by enhancing ice crystal production in clouds. When the ice crystals grow sufficiently, they become snowflakes and fall to the ground.

Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.



Safety

Research has clearly documented that cloud seeding with silver-iodide aerosols shows no environmentally harmful effect. Iodine is a component of many necessary amino acids. Silver is both quite inert and naturally occurring, the amounts released are far less than background silver already present in unseeded areas.

Effectiveness

Numerous studies performed by universities, professional research organizations, private utility companies and weather modification providers have conclusively demonstrated the ability for Silver Iodide to augment precipitation under the proper atmospheric conditions.

STATE OF THE CLIMATE

Every ten years, the National Oceanic and Atmospheric Association (NOAA) releases a summary of various U.S. weather conditions for the past three decades to determines average values for a variety of conditions, including, temperature and precipitation. This is known as the U.S Climate normal, with a 30-year average, representing the "new normal" for our climate. These 30-year normal values can help to determine a departure from historic norms and identify current weather trends.

The recently released 30-year average ranges from 1990 – 2020. Images in Figure 1 and 2 show how each 30-year average for the past 120 years compares to the composite 20th century average for temperature and precipitation. For the western U.S., the 1990-2020 average show much warmer than average temperatures, in comparison to the 100-year 20th century average. When comparing precipitation for the past 30 years to both the previous 30-year average and the 1901-2000 average, the American Southwest (including portions of Utah, Arizona, California and Nevada) has seen as much as a 10% decrease in average annual precipitation.

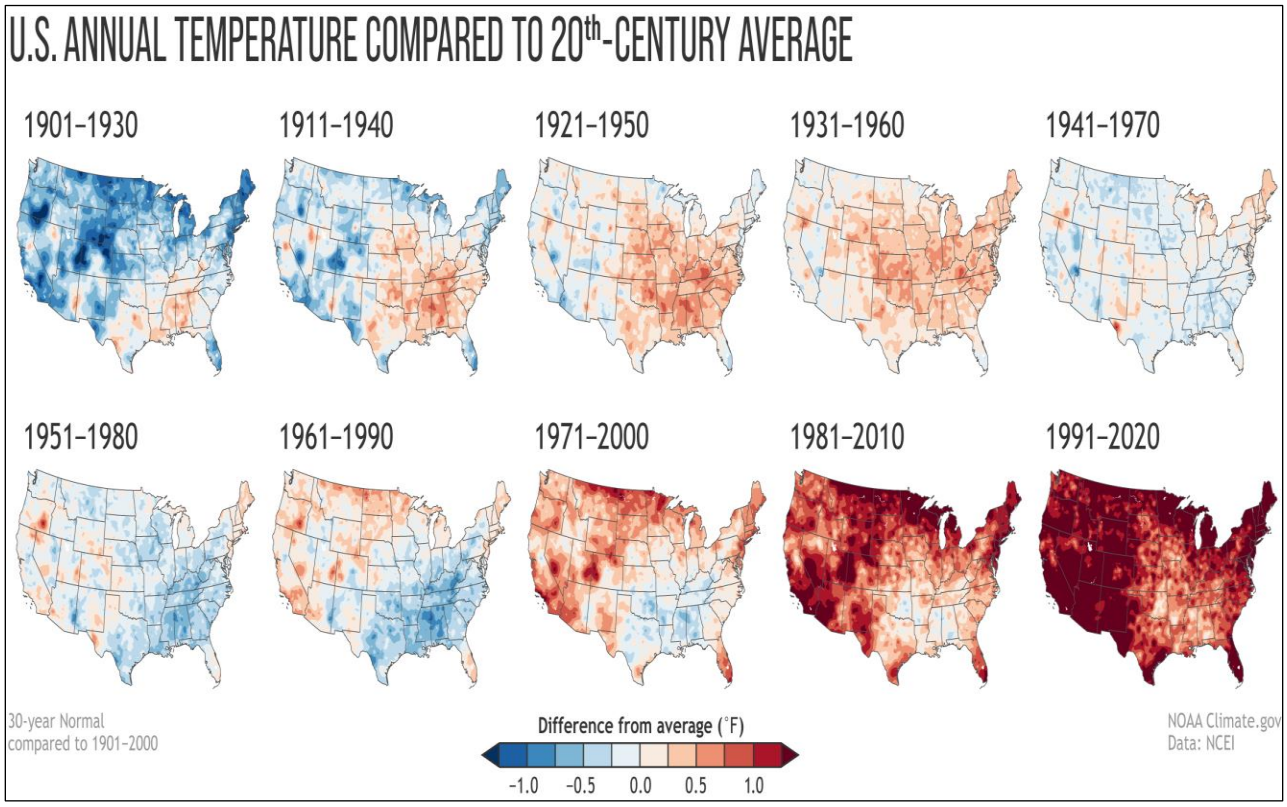


Figure 1 **U.S. Annual Temperature compared to 20th-Century Average**

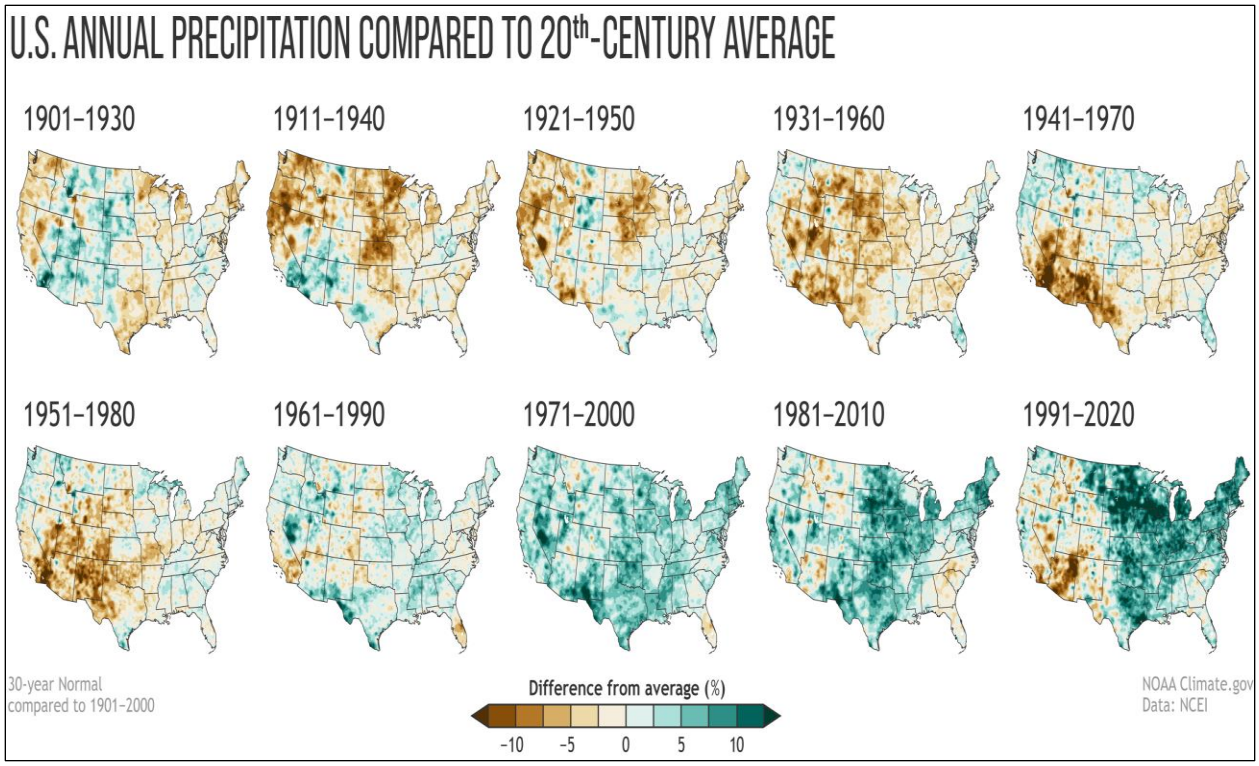


Figure 2 **U.S. Annual Precipitation compared to 20th-Century Average**

EXECUTIVE SUMMARY

In many past winter seasons, cloud seeding has been conducted in several different regions within central and southern Utah. Since the mid-1970s seeding has been concentrated in the mountainous watersheds from Millard and Sanpete Counties southward to the Pine Valley Mountains and Washington County and the headwaters of the Sevier River in Iron and Garfield Counties. The mountainous portions of Tooele and Juab Counties have been included as seeding target areas since 1988. The intended target areas of this program generally include terrain above 7,000 feet elevation.

The Southern and Central Utah Seeding Program utilizes approximately 70 ground-based, manually operated (Cloud Nuclei Generator, or CNG) sites, containing a 2% silver iodide solution. Cost sharing for the seeding program is provided by the Utah Division of Water Resources. Additionally, funds from the Lower Colorado River Basin States have resulted in early-season (November 1st-15th) and late season (March 16th - April 15th) extensions to the seeding program since 2010.

For this season a special three-county extension occurred in central Utah late in the season, to help alleviate the extreme drought brought on by significantly below average precipitation.

Precipitation and snowfall were well below normal during the 2020-2021 winter season. A total of 5,500 CNG hours were conducted during 21 storm periods for the core program this season, utilizing all of the budgeted hours. An additional 1,598 hours of seeding were conducted during two early-season and ten late-season storm periods for the Lower Basin Extension periods. An additional 220 hours of seeding were conducted for the special three-county extension in central Utah during late March and April during some of these same late-season events. There were no seeding suspensions during the 2020-2021 season.

Evaluations of the effectiveness of the cloud seeding program were made for both the past winter season and for all seeded seasons combined. These evaluations utilize SNOTEL records collected by the Natural Resources Conservation Service (NRCS) at selected sites within and surrounding the seeded target area, as well as some seasonal streamflow data. Analyses of the effects of seeding on target area precipitation and snow water content have been conducted for this seeding program, utilizing target/control comparison techniques.

Evaluation of December – March precipitation data demonstrate a long-term seasonal average increase of 12% for both Eastern Tooele County and the primary target areas of central and southern Utah. April 1st snowpack evaluations have demonstrated a similar 10% increase in Eastern Tooele County and a more conservative 4% increases for the central and southern Utah watersheds. As discussed in section 6.0 of the report, the precipitation evaluation results are stronger mathematically, and suggest roughly a 1.3-inch increase in seasonal precipitation in the target areas due to seeding. This would likely produce an average additional runoff of more than 70,000 acre-feet annually in these watersheds.

It is recommended that the currently designed winter seeding programs over the mountainous portions of central and southern Utah be continued. Routine application of weather modification technology each year can help stabilize and increase water supplies, both with surface and underground storage. NAWC recommends the following enhancements to optimize the program, and increase the program's effectiveness:

- Work with Sevier, Beaver and other non-participating counties to encourage their support of the program. This would permit for the installation of additional generators along critical areas of the central/southern mountain ranges.
- Provision for additional generators in key locations. As an example, Carbon County has agreed to increase their contribution to the program to cover the costs associated with finding and operating a new CNG site in the areas north and west of Scofield Reservoir.

1.0 INTRODUCTION

Since the mid-1970s, operational cloud seeding has been routinely conducted throughout the winter and early spring seasons over many of the mountainous watersheds of central and southern Utah. Water managers and others concerned about maintaining adequate water supplies have recognized that application of cloud seeding technology can be a viable method available to augment and help stabilize water supplies. By employing cloud seeding it could be possible to moderately increase the amount of precipitation and runoff beyond that which would have occurred naturally. Operations can be suspended in portions of or all of certain winter seasons that experience excessive amounts of precipitation. Cloud seeding suspensions, for example, were invoked in the 1982, 1983, 1993, 1995, 2005, 2008, 2010, 2011, 2017 and 2019 water years. Operations were suspended entirely in the 1984 water year due to abnormally wet conditions.

In a number of past winter seasons, cloud seeding has been conducted in many different regions within central and southern Utah. Since the mid-1970s seeding has been concentrated in the mountainous watersheds from Millard and Sanpete Counties southward to the Pine Valley Mountains and Washington County and the headwaters of the Sevier River in Iron and Garfield Counties. The mountainous portions of Tooele and Juab Counties have been included as seeding target areas since 1988. A map showing the current boundaries of these seeded target areas is provided in Figure 1.1. The target areas, generally terrain above 7,000 feet MSL, were selected as high-yield areas with substantial snowpack accumulation. These areas are the primary contributors to spring and summer streamflow. Figure 1.2 depicts the average annual precipitation for the State of Utah. This figure graphically demonstrates these higher-yield areas.

Traditionally, the sponsoring counties or water conservancy districts have contracted the cloud seeding program in central and southern Utah with the Utah Water Resources Development Corporation (UWRDC). The UWRDC, a non-profit organization, was formed in the 1950s to act as a liaison between the agencies desiring cloud seeding and the company providing the actual cloud seeding equipment and operations. North American Weather Consultants (NAWC) has been contracting with the UWRDC in this capacity. During the current water year, the State of Utah, through the Division of Water Resources, was again a co-sponsor of this program through 50% cost sharing.

Cloud seeding in Utah is regulated by the Utah Department of Natural Resources through the Division of Water Resources. Utah law requires that operators conducting cloud seeding have both a license and a site-specific permit for the area(s) to be seeded. The three Lower Colorado River Basin States (Arizona, California and Nevada), as in previous seasons, provided additional funding to extend the operational period in those areas of the southern target area, which contain tributaries to the Colorado River.

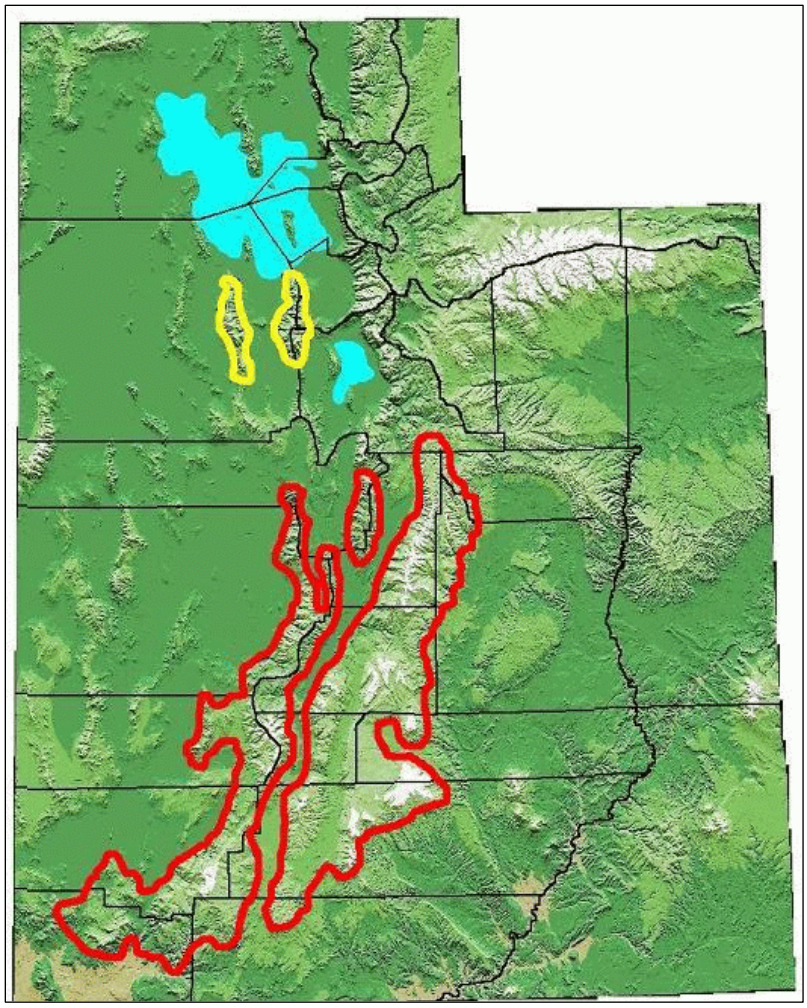


Figure 1.1 **Seeded target areas in central and southwestern Utah; Eastern Tooele Target (yellow) and Primary Target (red)**

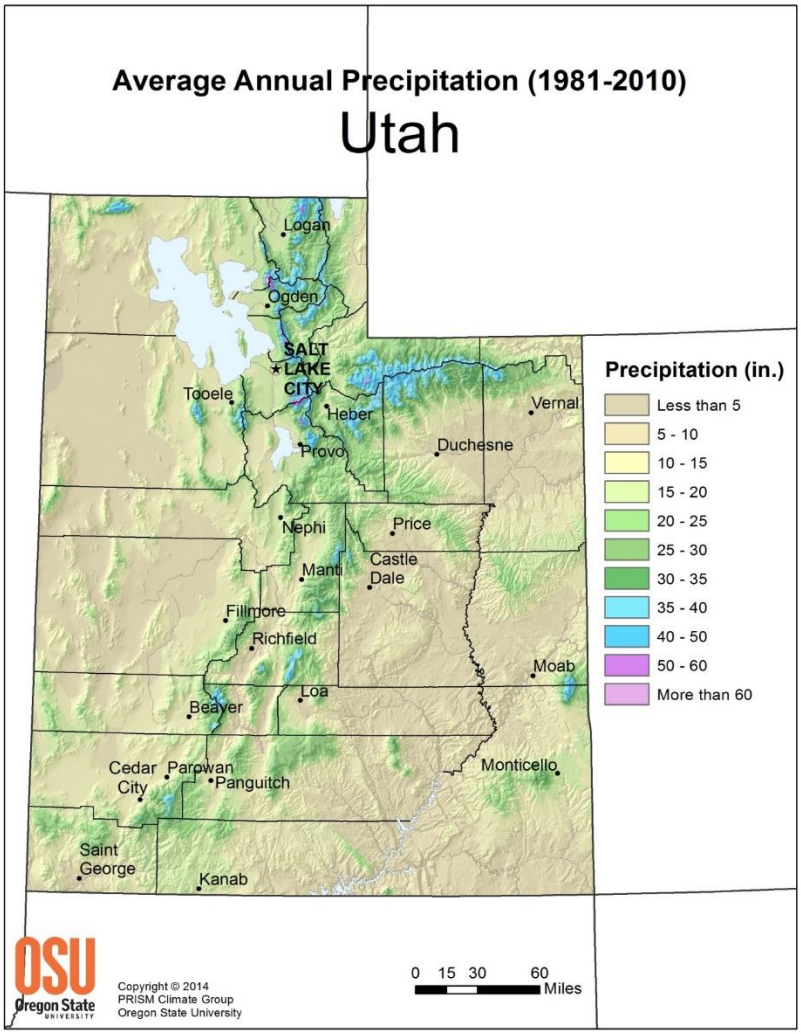


Figure 1.2 **Utah average annual precipitation**

1.1 Core Program and Extension Periods

As the demand for fresh water continues to grow in the southwest, the Colorado River is an extremely important component of the surface water supply in the region. Various Colorado River water interests (e.g. the Lower Basin States) have worked together in recent years to develop new or improved strategies aimed at enhancing the flow of the river better managing the water resources. One of the most promising strategies is increasing the use of cloud seeding for precipitation augmentation where and when viable seeding opportunities occur.

The primary Central and Southern Utah Seeding Program, funded by various Utah water interests and the Division of Water Resources, was active from November 16 – March 15 this season. The Central/Southern Utah Project was one of two Utah projects selected to receive supplemental Lower Basin funding. Via an agreement between the Lower Basin States and Utah's Division of Water Resources, supplemental funds for extension of the operational seeding period for a portion of the Central/Southern Project have been provided. The extension periods funded by Lower Basin States were from November

1-15 and March 16 – April 15 during the 2020-2021 winter season. Thus, additional benefit was realized by some of the Utah sponsors at no additional cost to them.

1.2 Installation and Operation of Icing Rate Meters

An earlier agreement with the three Lower Basin States provided funds to purchase some hardware for three remote icing rate meters. The Lower Basin States provided funds in the 2009 agreement to install and operate two of these sites beginning during the 2009-2010 winter season. One site was installed in central Utah in conjunction with a Utah Department of Transportation site (Skyline), a second site was established at the Brian Head ski area in southern Utah. Beginning with the 2012-13 winter season, a third icing meter site has been active at Dry Ridge in the Uintas (within the High Uintas seeding program target area). The icing rate meters detect the presence of supercooled liquid water (SLW) cloud droplets embedded in naturally occurring winter storms. These droplets are the target of the cloud seeding operations. Funds from the Lower Basin States are also provided for the analysis of the ice detector data to improve understanding of when/where SLW occurs in cold-season storm events. The Brian Head and Dry Ridge sites remained in operation this season, while the Skyline site was decommissioned due to re-allocation of funding. A separate report will once again cover the analyses of data collected from these sites.

2.0 PROJECT DESIGN

2.1 Background

Evaluations of this long-standing operational seeding project have consistently indicated increases in wintertime precipitation during the periods in which cloud seeding was conducted. Statistical analyses have suggested seasonal increases in precipitation that may be attributed to the cloud seeding program, averaging between 5% and 15% (Griffith et al., 2009). Operational procedures for Central/Southern Utah cloud seeding program utilize the basic principles of applying cloud seeding technology that have been shown to be effective during more than 40 years of wintertime cloud seeding for the mountainous regions of Utah. Continued increases in availability of weather data and forecast products have led to improved seeding opportunity recognition capabilities, and continued analysis of the effectiveness of operational cloud seeding projects is leading to improved confidence in the accuracy of the long-term average effects of the Central/Southern Utah Program. NAWC has incorporated observational, seeding method and evaluation enhancements into the project when they are believed to be of practical value to the project.

2.2 Seedability Criteria

Project operations have utilized a selective seeding approach, which has proven to be the most efficient method, providing the most cost-effective results. Selective seeding means that operations are conducted only during storms (or portions of storms) when seeding is likely to be effective. These decisions are based on several criteria, which determine the seedability of the storm. The criteria deal with meteorological characteristics (temperature, stability, wind flow and moisture content) associated with winter cloud systems. Table 2-1 provides the seeding criteria which NAWC has established for the southern/central Utah winter cloud seeding program.

Seeding cannot be effective unless the seeding material reaches portions of clouds equal to or colder than the warmest activation temperature (near -5°C) for silver iodide. This will generally be accomplished if the cloud base is at a lower elevation than the mountain crest and no temperature inversions or stable layers exist between the elevation of the cloud seeding generator and the cloud base. There were some storm events during the season where the cloud temperatures were too warm for seeding to be effective according to NAWC's operational criteria and were therefore not seeded. For reference, a brief summary of NAWC's operational criteria is as follows:

- Cloud bases are below mountain barrier rest.
- 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 inversion 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 than -15°C (5°F).

The existence of low-level stability can inhibit the effects of seeding by trapping silver iodide particles released from ground-based sources and preventing them from traveling to portions of the cloud where they can aid in nucleation and eventual precipitation production. Griffith et al., (2013) provides additional information on the seedability of winter storms.

2.3 Equipment and Project Set-Up

During the Fall of 2020, following a period of off-season maintenance, NAWC technicians re-installed the ground-based cloud seeding generators at sites selected to produce seeding plumes over the target areas in various wind situations. The target areas are discussed in more detail in Section 4.0. The seeding generator site locations, approximately 70 in all, are shown in Figure 2.1. Information on these locations is provided in Table 2-2.

Eleven ground-based seeding sites were available in eastern Tooele County (ET) during the season, located throughout the Tooele Valley from Erda and Grantsville southward to Faust, with additional sites to the west of the Stansbury Range, in Skull Valley. These locations allow for targeting of this portion of the seeding target area (Oquirrh and Stansbury Mountains) during a variety of wind flow situations.

The second seeded target group is referred to as the Primary Target (PT). This target area covers a large portion of central and southwestern Utah, including the principal mountain ranges listed below.

- Wasatch Range - northeast of Nephi
- Wasatch Plateau - east of Mt. Pleasant to east of Manti
- San Pitch Mountains - east of Levan to Gunnison
- Fish Lake Hightop Plateau - east of Koosharem
- Pavant Range - east of Fillmore to Cove Fort
- Tushar Mountains - east of Beaver
- Sevier Plateau - east of Salina to Panguitch
- Valley Mountains - east of Scipio
- Paunsaugunt Plateau - east of Panguitch and Hatch
- Markagunt Plateau - east of Paragonah to Brian Head
- Pine Valley/Harmony Mountains - southwest of Cedar City to St. George
- Kolob Terrace - south of Cedar City to Springdale

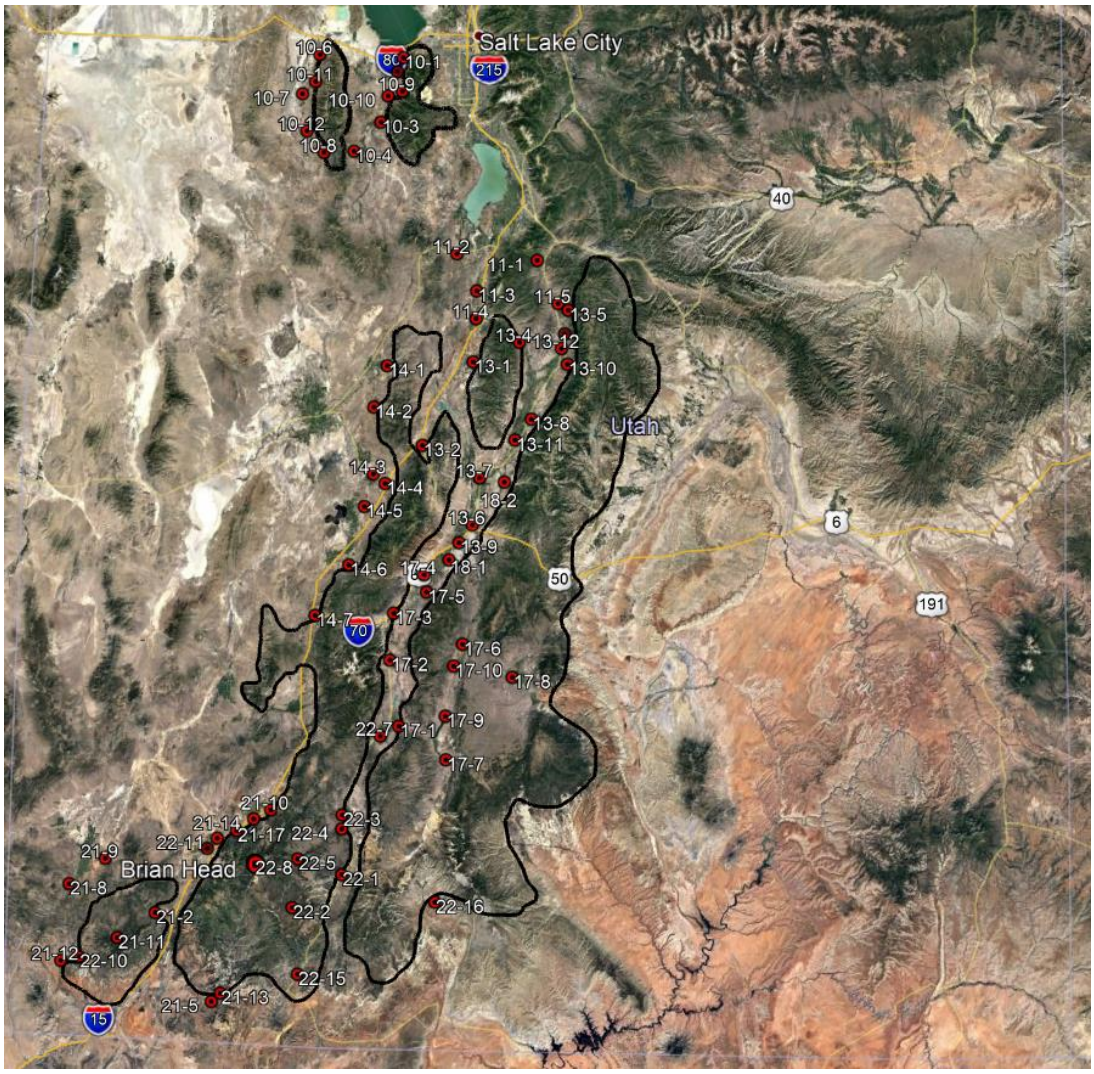


Figure 2.1 **Target areas and seeding site locations**

Table 2-2
Seeding Site Locations

Site Number	Name	Latitude (N)	Longitude (W)	Elevation (feet)
10-1	Lakepoint	40°40.85’	112°15.85’	4250
10-2	Erda	40°37.50'	112°16.97'	4415
10-3	Stockton	40°26.12'	112°21.18'	5234
10-4	Clover	40°19.50'	112°28.75'	5342
10-6	Skull Valley North	40°41.11'	112°40.10'	4289
10-7	Skull Valley Central	40°32.20'	112°44.74'	4390
10-8	Terra	40°19.12'	112°37.60'	5166
10-9	Pine Canyon	40°33.09'	112°15.15'	5095
10-10	Settlement Canyon	40°31.14’	112°18.16’	5140
10-11	Skull Valley #3	40°35.00’	112°41.00’	4300
10-12	Skull Valley #4	40°23.87’	112°42.92’	4890
11-1	Birdseye	39°55.70'	111°34.08'	5600
11-2	Elberta	39°57.12'	111°57.72'	4732
11-3	Mona	39°48.93’	111°51.61’	4943
11-4	Nephi West	39°42.78'	111°51.56'	5042
11-5	Hideaway Valley	39°46.32'	111°27.90'	6300
13-1	Levan	39°33.17'	111°52.06'	5286
13-3	Fairview	39°39.61’	111°25.87’	6125
13-4	Fountain Green	39°37.69'	111°38.88'	5985
13-5	Milburn	39°44.88'	111°24.96'	6787
13-6	Salina	38°57.22'	111°51.21'	5190
13-7	Centerfield	39°07.60'	111°49.43'	5100
13-8	Ephraim	39°20.73'	111°34.95'	5626
13-10	Mt. Pleasant	39°32.46'	111°27.03'	5981
13-11	Manti	39°16.08'	111°39.51'	5505
13-12	Fairview South	39°36.44'	111°26.71	5855
14-1	Leamington	39°31.99'	112°16.92'	4721
14-2	Oak City	39°22.76'	112°20.43'	5059
14-3	McCornick	39°07.95'	112°20.01'	4848
14-4	Holden	39°05.92'	112°16.49'	5077
14-5	Fillmore	39°00.71’	112°22.30’	4879
14-6	Kanosh	38°47.71'	112°26.20'	5048
14-7	Cove Fort	38°36.35'	112°35.44'	5942
17-1	Kingston	38°12.40'	112°11.33'	6018
17-2	Marysvale	38°26.98'	112°13.72'	5870
17-3	Joseph	38°37.34'	112°13.00'	5435
17-4	Richfield	38°45.96’	112°04.68’	5296
17-5	Annabella	38°42.17'	112°03.77'	5316
17-6	Koosharem	38°30.87'	111°53.13'	6973
17-7	Antimony	38°05.29'	111°57.25'	6661

Site Number	Name	Latitude (N)	Longitude (W)	Elevation (feet)
17-8	Loa	38°23.83'	111°38.89'	7052
17-9	Angle	38°14.91'	111°57.65'	6415
17-10	Greenwich	38°26.00’	111°55.54’	6882
18-1	Sigurd	38°50.52’	111°57.90’	5220
18-2	Mayfield	39°06.97'	111°42.52'	5550
21-1	Cedar City West	37°43.84'	113°04.53'	5525
21-2	New Harmony	37°29.05'	113°18.85'	5355
21-5	Rockville	37°09.70'	113°02.35'	3737
21-8	Enterprise	37°34.50'	113°43.99'	5345
21-9	Newcastle	37°40.61'	113°33.73'	5242
21-10	Paragonah	37°52.98’	112°46.56’	5880
21-11	Pine Valley	37°23.05'	113°29.57'	6579
21-12	Gunlock	37°17.16'	113°45.88'	3638
21-13	Springdale	37°11.65'	112°59.83'	3987
21-14	Parowan	37°50.88'	112°49.56'	5980
21-17	Summit	37°48.04'	112°55.96'	6009
22-1	Hatch	37°39.20'	112°26.00'	6922
22-2	Duck Creek	37°31.50’	112°39.80’	8451
22-3	Spry	37°52.43'	112°26.24'	6564
22-4	Panguitch	37°52.38'	112°23.88'	6610
22-5	Panguitch Lake	37°42.39’	112°38.47’	8255
22-7	Circleville	38°10.27'	112°16.03'	6082
22-8	Brian Head Summit	37°41.64'	112°50.76'	9591
22-9	Brian Head Store	37°41.58'	112°51.00'	9700
22-10	Dammeron Valley	37°18.26'	113°40.56'	4546
22-11	Enoch	37°46.44'	113°01.55'	5566
22-15	Orderville	37°16.62’	112°38.10’	5470
22-16	Henrieville	37°33.72’	112°59.64’	6000

The primary target area reaches from eastern Juab County in central Utah, southward to the northern portions of Washington and Kane Counties in southwestern Utah.

There are approximately 60 seeding generator sites available for the primary target areas. These generators extended roughly in north to south lines west of the target areas in eastern Juab and Millard well as throughout Sanpete, Sevier and Piute Counties. Further south, generators were located in Iron, Garfield, Kane, and Washington Counties. This equipment array provides various seeding options regardless of wind direction, as some generators are nearly always upwind of a portion of the target area during storms. It should be noted that winds during winter storms in Utah typically blow from the west toward the east, most commonly from the southwest before frontal passages and from the northwest following cold frontal passages.

The cloud seeding equipment at each site includes a cloud seeding generator unit and a propane gas supply tank. The seeding solution consists of two percent (by weight) silver iodide (AgI), complexed with small portions of sodium iodide and para-dichlorobenzene, in solution with acetone. This particular solution is used because it is formulated specifically to be a fast-acting nucleation agent via the condensation-freezing mechanism, rather than via the slower contact nucleation mechanism. This is an important characteristic, given the relatively narrow mountain barriers within the cloud seeding target areas in Utah. The 2% silver iodide solution has been used throughout most of the history of the program.

The seeding units are manually operated by a local operator igniting propane in a burn chamber, and then adjusting the flow of the seeding solution into the burn chamber through a flow rate meter. The propane gas pressurizes the solution tank, which allows the solution to be forced into the burn chamber. The regulated seeding solution is sprayed into the propane flame, where microscopic silver iodide crystals are formed through the combustion process. The silver iodide is released at a rate of eight grams per hour, and after combustion it produces these ice-forming nuclei crystals, which closely resemble natural ice crystals in structure. These crystals become active as ice-forming nuclei beginning at temperatures near -5°C (23°F) in-cloud. Since experience has indicated that seeding is most effective within a particular temperature range (Griffith et al., 2013), the seeding generators were operated only during those periods when the temperatures within the cloud mass were between about -5 and -25°C (+23 to –13°F). For the seeding to be effective, the AgI crystals must become active in the cloud region which contains supercooled liquid water droplets sufficiently far upwind of the mountain crest so that the available supercooled liquid water can be effectively converted to ice crystals which will then grow to snowflake sizes and fall out of the cloud onto the mountain barrier. If the AgI crystals take too long to become active, or if the temperature upwind of the crest is too warm, the plume will pass from the generator through the precipitation formation zone and over the mountain crest without freezing the cloud drops in time to affect precipitation in the desired area.

Most storms that affect Utah's mountains are associated with synoptic (large-scale) weather systems that move into Utah from the southwest, west, or northwest. They usually consist of a frontal system and/or an upper trough, with the air preceding the front or trough flowing from the south or southwest. As the front/trough passes through the area, the wind flow changes to the west, northwest, or north and the atmosphere cools. Clouds and precipitation may precede the front/trough passage, or they may mostly occur along the boundary of the colder air mass that moves into the region, and in some cases, continuing in the airmass behind the front or trough. For that reason, the seeding generators were situated to enable effective targeting in varying wind flow regimes, primarily ranging from southwesterly to northwesterly. Winds in meteorology are reported from the direction with which the winds are blowing. For example, a southwest wind means the winds are blowing towards the northeast.

The core 2020-2021 cloud seeding program for central and southern Utah began on November 15, 2020 and ended on March 15, 2021. Time extensions, funded by the Lower Basin States, covered the periods of November 1-15, 2020 and March 16 – April 15, 2021 for the portions of the target area that potentially contribute runoff to the Colorado River. The seeding generators located in the central valley from approximately Milburn to Hatch were used in this program extension, as well as a few sites in the area near Koosharem, Antimony, and Loa, plus those in the vicinity of Brian Head and the Pine Valley Mountains. Seeding from the central valley sites would be expected to produce positive seeding effects on both the western and eastern slopes of the Wasatch Plateau. The eastern slopes of the Wasatch Plateau are tributary to the Colorado River. Seeding from these sites and those near Antimony would

provide increases in precipitation on the western and eastern slopes of the Escalante Mountains (eastern slopes tributary to the Colorado River) and the Thousand Lakes and Boulder Mountains (also tributary to the Colorado River). Figure 2.2 is a map of the areas that contribute runoff to the Colorado River, areas where early and late-season time extensions to the seeding program were funded by the Lower Basin States. These areas are also included as part of the core program and so are subject to seeding operations during the entire seasonal period.

2.4 Suspension Criteria

NAWC has a standing policy of operating within guidelines adopted to ensure public safety. Accordingly, NAWC, working in conjunction with the Utah Division of Water Resources, has developed criteria and procedures for the suspension of cloud seeding operations (detailed in Appendix A). Due to a large number of wildfires during the past several years, NAWC's suspension criteria included situations that might impact several burn areas located with the central/southern Utah target areas during periods that might be conducive to debris flows. There were no seeding suspensions during the 2020-2021 season.

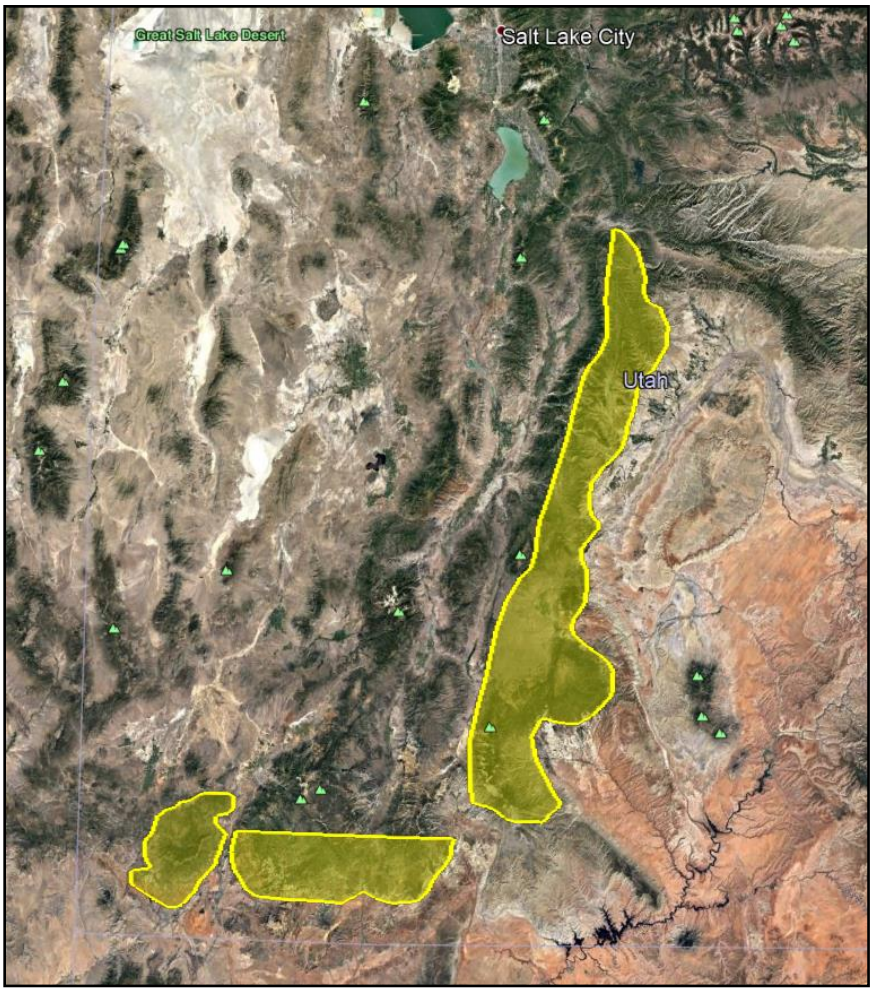


Figure 2.2 **Portions of the Southern/Central Utah Program that contribute to the Colorado River**

3.0 WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

NAWC maintains a fully equipped project operations center at its Sandy, Utah headquarters. Meteorological information is acquired online from a wide variety of sources, including some subscriber services. This information includes weather forecast model data, surface observations, rawinsonde upper-air observations, satellite images, NEXRAD radar information, and local webcams. This information helps NAWC meteorologists to determine when conditions are appropriate for cloud seeding. Each of NAWC's meteorologists also has access to these same products at home, allowing continued monitoring and conduct of seeding operations outside of regular business hours. Figures 3.1–3.3 show examples of some of the available weather information that was used in this decision-making process during the 2020-2021 winter season.

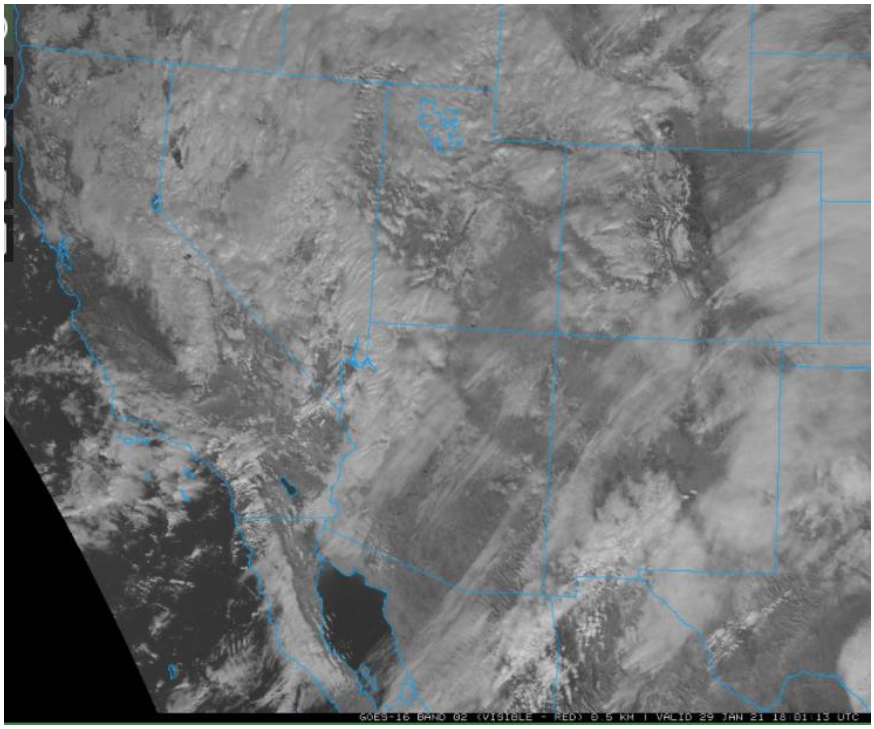


Figure 3.1 **Visible spectrum satellite image at 1100 MST January 29, 2021 as a trough moved across Nevada and into Utah.**

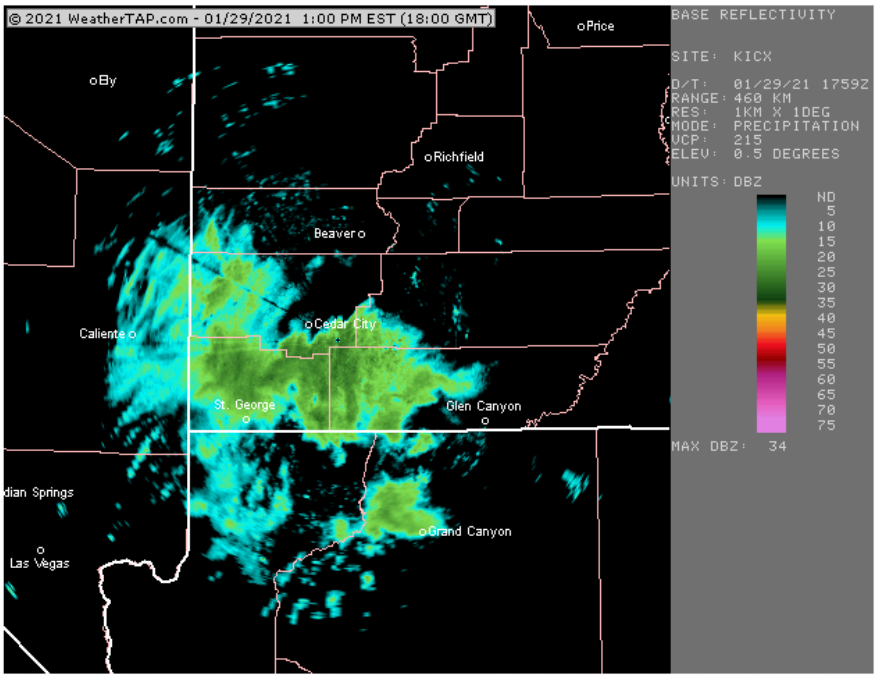


Figure 3.2 Cedar City weather radar image at 1100 MST January 29, corresponding to satellite image in Fig 3.1

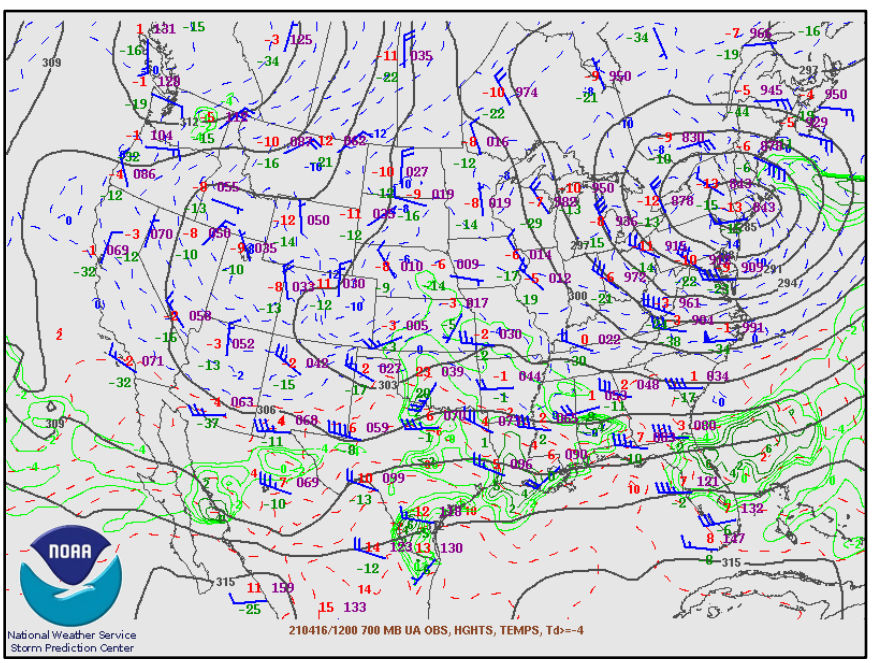


Figure 3.3 700 mb map at 0600 MDT on April 16, 2021, showing winds, temperatures, and moisture values at that level.

Global and regional forecast models are an important tool for operational cloud seeding decisions. Models forecast a variety of parameters at different levels of the atmosphere, including winds, temperatures, moisture, and surface parameters such as accumulated precipitation. An example of a forecast from the North American Model (NAM) is shown in Figure 3.4.

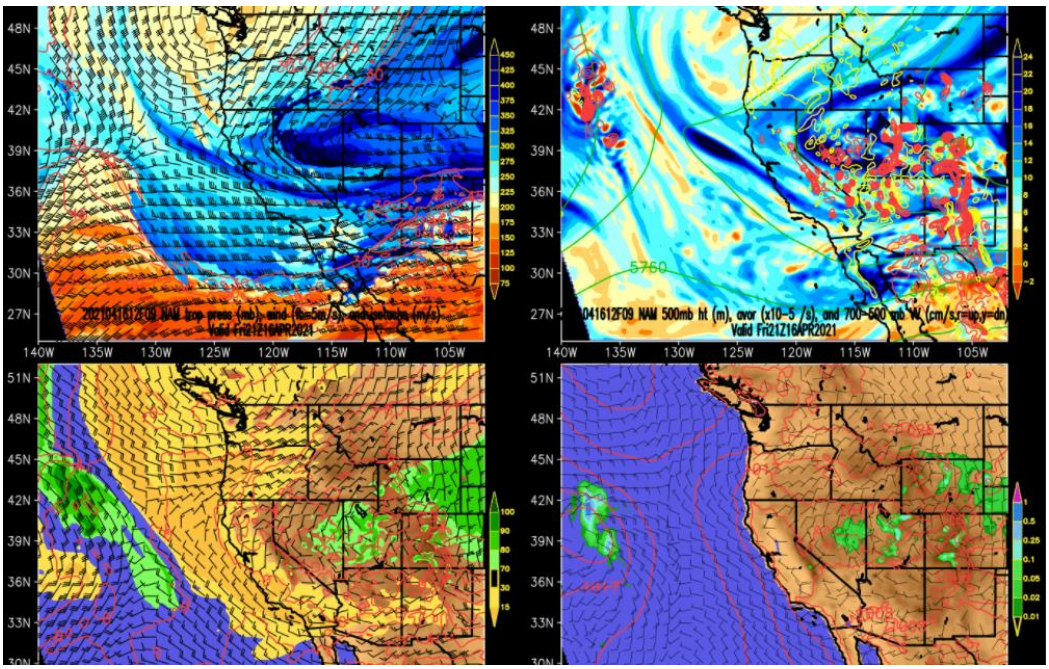


Figure 3.4 NAM model forecast (4-panel plot) during a storm event on April 16, 2021.

Figure 3.5 provides predictions of ground-based seeding plume dispersion for a storm period in central and southern Utah using the National Oceanic and Atmospheric Administration's HYSPLIT model (information provided in Appendix B). This model assists in estimating the horizontal and vertical spread of a plume from potential ground-based seeding sites in real-time, based on wind fields contained in the weather forecast models.

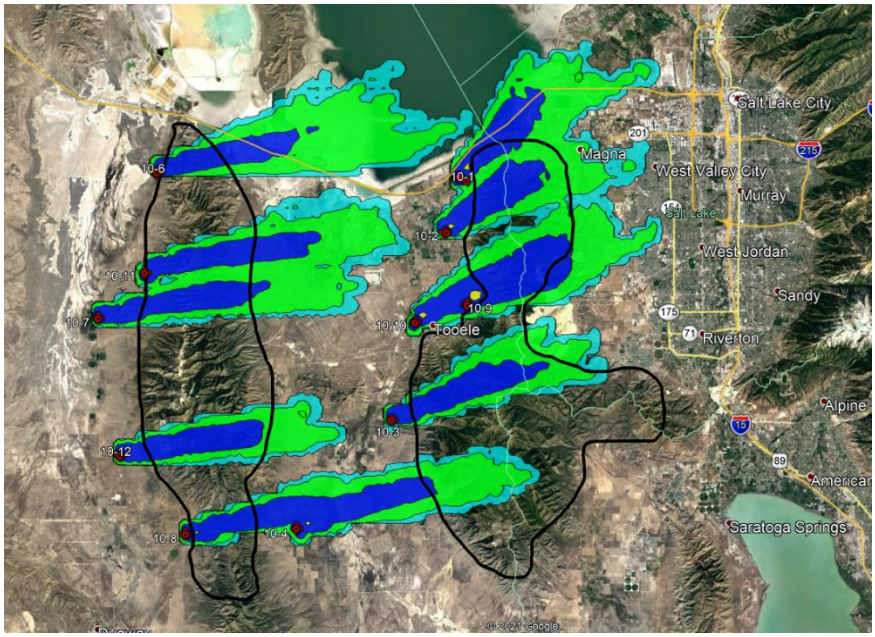


Figure 3.5 **HYSPLIT plume dispersion forecast from a seeding storm event on the night of January 29-30, 2021 (less than 1 hour)**

An agreement between the three Lower Colorado River Basin States and the Utah Division of Water Resources has provided continued funding for icing rate meters and special precipitation detectors at two sites in Utah. One of them is located in the Central/Southern Utah project area, at Brian Head Ski Resort in southwestern Utah. The ice detectors are used to measure the occurrence of supercooled liquid cloud droplets, useful in making real-time seeding decisions, as well as for later analysis. The icing meter cycles when a certain amount of icing accumulates on a small probe. The probe is then heated briefly to de-ice the probe. Multiple cycles are indicative of likely favorable seeding situations, assuming that the other seeding criteria, especially temperature, are met. Figure 3.6 provides a photograph of an installation at Brian Head, and Figure 3.7 is a close-up photo of the instrumentation at this site.

Figure 3.6 Icing meter suite at Brian Head Ski Resort.

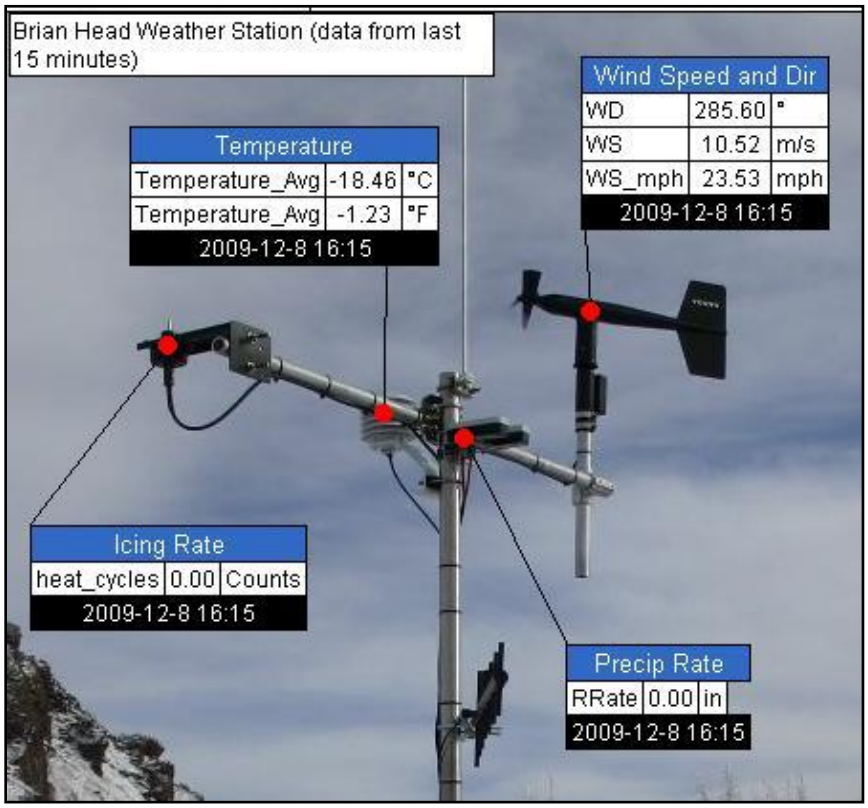


Figure 3.7 Close-up photo of the special instrument suite at Brian Head.

4.0 OPERATIONS

A total of 21 storm events were seeded during the core program contract period (November 15th – March 15th), and 12 additional events were seeded during the fall and spring extension periods (November 1st to 15th, March 16th – April 15th). There were two seeding opportunities during the November 1-15 portion of the Lower Basin States extension this season and ten during the March – April portion. In all, there were three storm events seeded in November, four events in December, five in January, eight in February, eight in March, and five in April. For the regular contract period, all budgeted 5,500 generator hours were utilized. For the Lower Basin extension, there was an additional 1,598 generator hours of seeding conducted. A special 3-county extension in central Utah during late March and April, intended to help alleviate severe drought conditions, resulted in an additional 220 generator hours of seeding. Figure 4.1 shows cumulative seeding hours for the core program this season. Table 4-1 shows the dates and number of CNGs used for each of the storm events, and Appendix B shows detailed usage for the individual CNG sites.

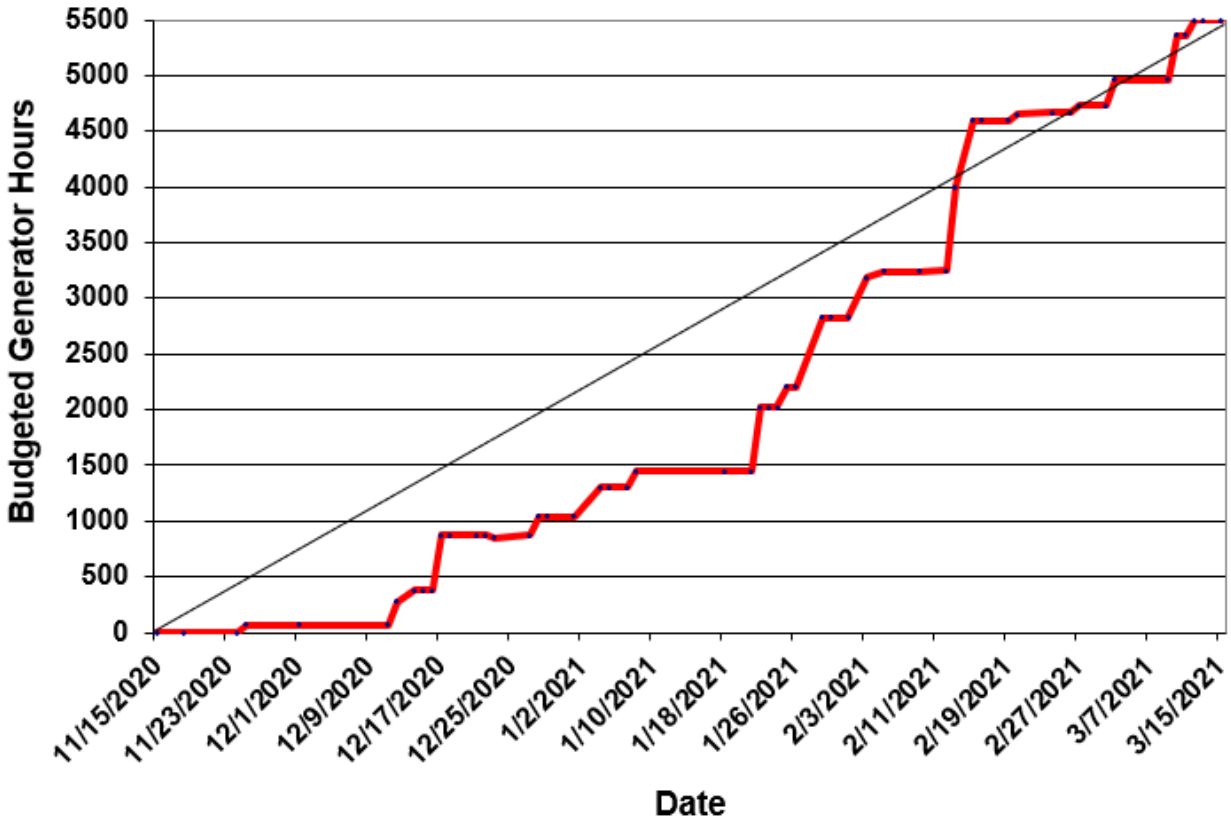


Figure 4.1 **Cumulative and budgeted seeding hours for the southern/central program during the 2020-2021 season. Red line shows actual usage, while the black diagonal line depicts a linear usage of budgeted hours.**

Table 4-1
Storm dates and generator usage, 2020-2021 season

Storm No.	Date(s)	Number of CNG Sites	Number of Generator Hours			
			Primary Contract	Lower Basin Extension	3-County Extension	Total Hours
1	November 7-9	29		584.5		
2	November 13-14	17		210.75		
3	November 25-26	6	64.25			
4	December 12	27	212.75			
5	December 14-15	13	98.25			
6	December 17-18	42	499			
7	December 28-29	14	167			
8	January 4-5	29	259			
9	January 8-9	13	145			
10	January 22-24	39	577.75			
11	January 25-26	11	18.25			
12	January 29-30	57	624.5			
13	February 3-4	33	359			
14	February 5-6	9	50.5			
15	February 12	2	7.5			
16	February 13-14	48	751.75			
17	February 15-17	20	596			
18	February 20	14	55.5			
19	February 24	4	15.75			
20	February 27	12	70			
21	March 3-4	17	228.25			
22	March 10-11	19	395.5			
23	March 12-13	17	142.5			
24	March 15-16	9		99.25		
25	March 20-21	27		355.75		
26	March 21	5		22.75		
27	March 23	2		12.5		
28	March 26	21		112	30.5	
29	April 14	6		42.25		
30	April 15	24		158.25	12.25	
31	April 16	6			49	

Storm No.	Date(s)	Number of CNG Sites		Number of Generator Hours		
			Primary Contract	Lower Basin Extension	3-County Extension	Total Hours
32	April 26	11			91	
33	April 27	4			37.25	
Total			5,500	1,598	220	7,318

As of April 1st, 2021, SNOTEL observations showed somewhat variable numbers for snowpack and cumulative water year precipitation, all below the seasonal average. The cumulative precipitation percentages of normal were lower than those of snowpack. Part of this differences is expected due to the differences between the median (used as a normal for snowpack) and mean (used as a normal for precipitation). The lowest percentages overall for the season were in southwestern Utah, and the highest in Tooele County. The April 1 data are summarized in Table 4-2.

Table 4-2
Snowpack and Precipitation Percentages on April 1, 2021

River Basin	No. of Reporting Stations	Snow Water Percent of Median	Water Year Precipitation Percent of Average
Tooele County	4	93%	74%
Price - San Rafael	7	74%	67%
Beaver River	3	86%	75%
Upper Sevier River	13	81%	70%
Southwestern Utah	8	63%	59%

Figure 4.2 provides the percent of median values of April 1 snow water content for Utah. Figures 4.3 – 4.5 show October 1, 2020 – April 1, 2021 snow water equivalent, accumulated precipitation, and normal values for three SNOTEL sites.

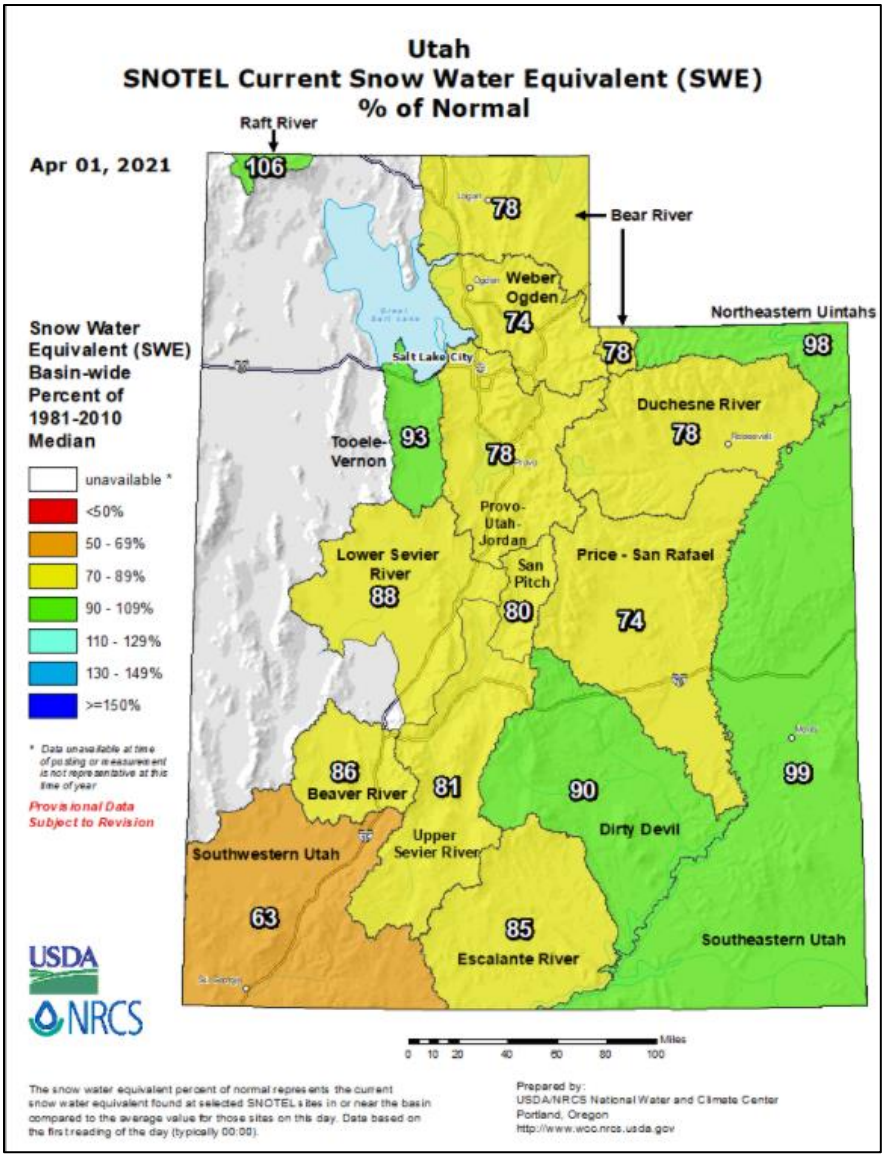


Figure 4.2 **Snow water content in Utah on April 1st, 2021 (percent of median)**

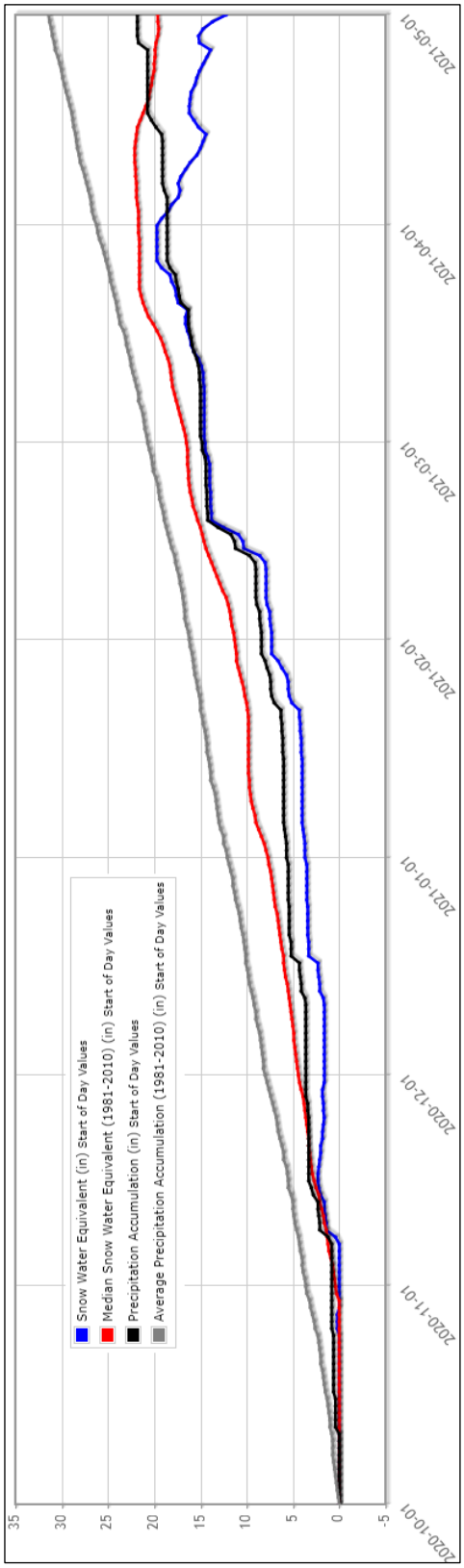


Figure 4.3 **SNOTEL graph for Rocky Basin Settlement in Tooele County. The black and blue lines represent accumulated precipitation and snow water content for the current season, respectively. The grey and red lines are the corresponding 30-year averages.**

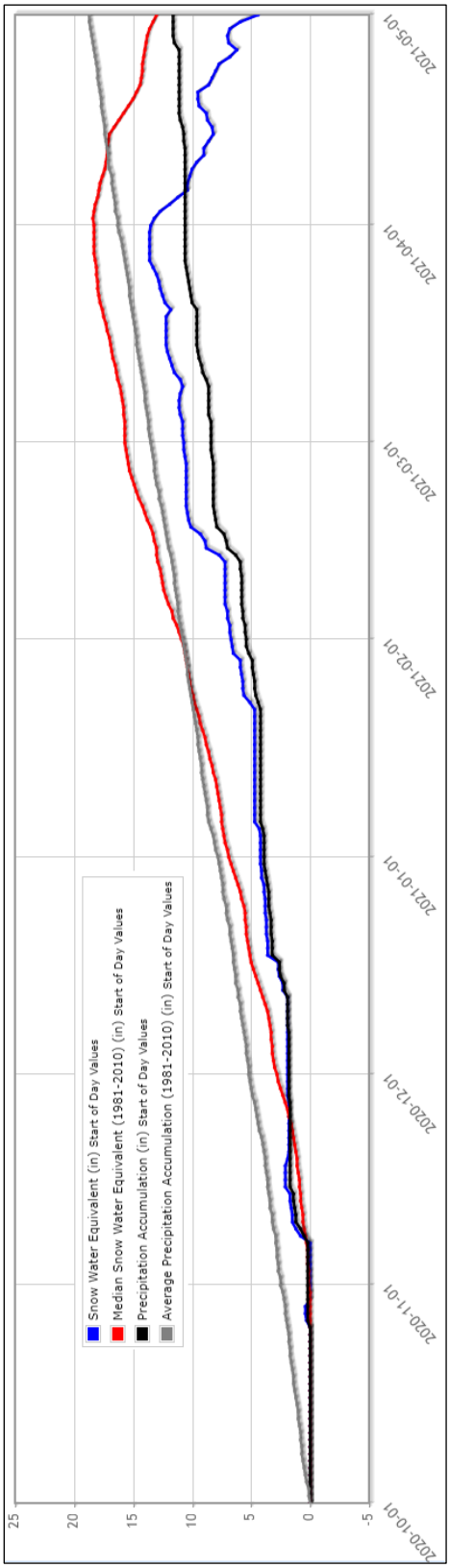


Figure 4.4 **SNOTEL graph for Mammoth-Cottonwood in central Utah. The black and blue lines represent accumulated precipitation and snow water content for the current season, respectively. The grey and red lines are the corresponding 30-year averages.**

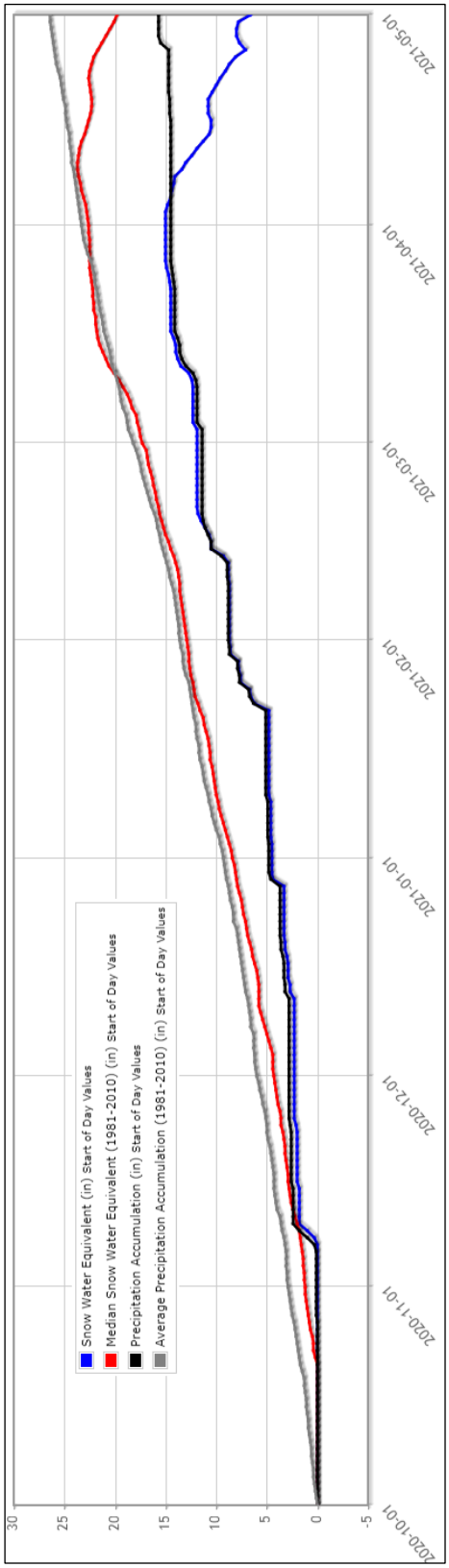


Figure 4.5 **SNOTEL graph for Midway Valley in southwestern Utah. The black and blue lines represent accumulated precipitation and snow water content for the current season, respectively. The grey and red lines are the corresponding 30-year averages.**

4.1 Operational Procedures

In operational practice, an approaching storm was monitored at the NAWC operations center in Sandy with the aid of continually updated online weather information. Outside typical business hours, NAWC's meteorologists monitored the weather information using computer systems at their residences. If the storm parameters met the seedability criteria presented in Table 2-1 of Section 2 and no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators was ignited and adjusted as conditions required. Seeding continued as long as conditions were favorable and precipitating clouds remained over the target areas. In a normal sequence of events, certain generators would be used in the early period of the storm passage, some of which might be turned off as the wind directions at various levels of the atmosphere changed, while others were used later to target the area in response to the evolving wind pattern. Some generator sites, due to their location, were used in a wider variety of wind flow situations than others and were thus used more often.

4.2 Operational Summary

A synopsis of the atmospheric conditions during operational seeding periods is provided below. All times reported are local, either in MST or MDT. This synopsis describes seeded storm periods, as well as some significant storm periods that were not seeded.

November 2020

November was quite dry over most of the target areas, except some areas near Brian Head which were near average. Figure 4.6 shows precipitation as a percentage of the average (mean) monthly values across the region in November. There were three seeded storm periods in November, the first two of these being for the Lower Basin early season extension period.

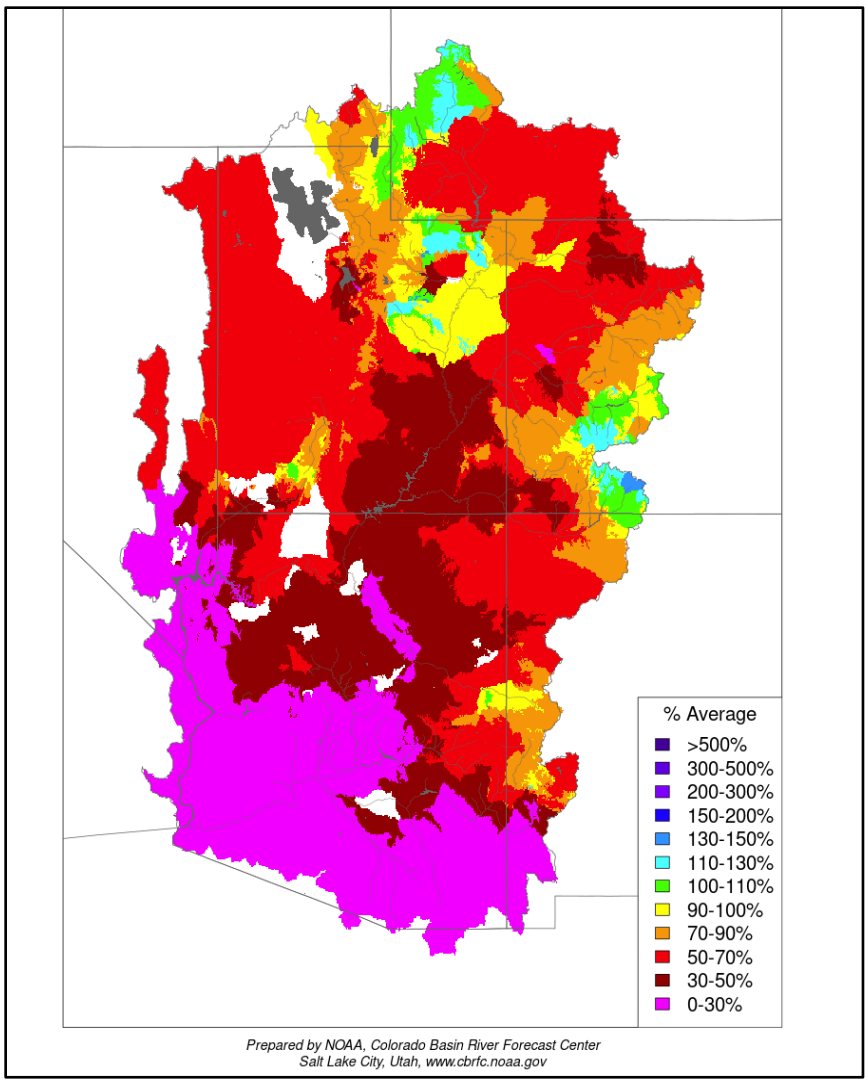


Figure 4.6 **November 2020 precipitation, percent of normal**

A deep trough moving across California and Nevada brought cooling and moistening conditions on November 7, with favorable conditions for seeding initially in southwestern Utah beginning on the night of November 7-8. The Brian Head ice detector site recorded a good amount of icing activity overnight (see Figure 4.7). On the 8th, favorable conditions spread across much of southern and central Utah, with a mix of convective and orographic precipitation and 700 mb temperatures around -8° to -10°C in south-southwesterly flow. After widespread seeding operations on November 8 over roughly the southern half of the state, more limited operations continued overnight (November 8-9) for most southern portions of the target area with light southerly flow and light snowfall continuing. Cooling temperatures and light orographic snowfall continued into November 9 as the winds shifted to the northwest, and the seeding site array was adjusted to target favorable areas (especially southwestern Utah near Brian Head) in northwesterly flow. The 700 mb temperature cooled to around -12°C. Snowfall gradually decreased later on November 9, and all seeding was terminated in the evening. Precipitation totals from this extended, approximately 48-hour storm event were between about 0.5 – 1.5 inches in the

seeded portions of the target areas (from about Piute County southward) with the highest totals up to about 1.8 inches near Brian Head.

The next storm event, on November 13-14, affected mainly the northern half of the area, with a fast moving cold frontal passage on the night of the 13-14th. Seeding was conducted from Sanpete down to Piute County to affect the eastern (extension) portions of the target area. Winds were quite strong with this event, and the 700 mb temperature dropped to -10°C or below following the frontal passage. There was a period of convection with the frontal passage, including some lightning at least in portions of northern Utah. By the morning of the 14th, snowfall has generally ended except in more northern portions of central Utah target areas (Sanpete County) where orographic snow showers continued. Seeding ended early farther south but continued until midday in northern areas. Precipitation patterns were highly orographic with this system, with very little precipitation in the valleys but decent amount in some target areas. Totals ranged from about 0.4 to 0.8 inches of SWE in the north to around 0.2 inches along the southern edge of the seeded area, in the area of Piute and Wayne counties.

After the beginning of the core program for southern/central Utah, the latter portion of November brought some very weak systems, with little seeding opportunity. The only seeded system during this period was a cold frontal passage on the night of November 25-26. This system affected Tooele County, where some brief lake effect snow developed, as well as northern portions of central Utah. Seeding was conducted from a few of the more favorably positioned sites in these areas, and precipitation totals were limited to about 0.1 inches some SNOTEL sites.

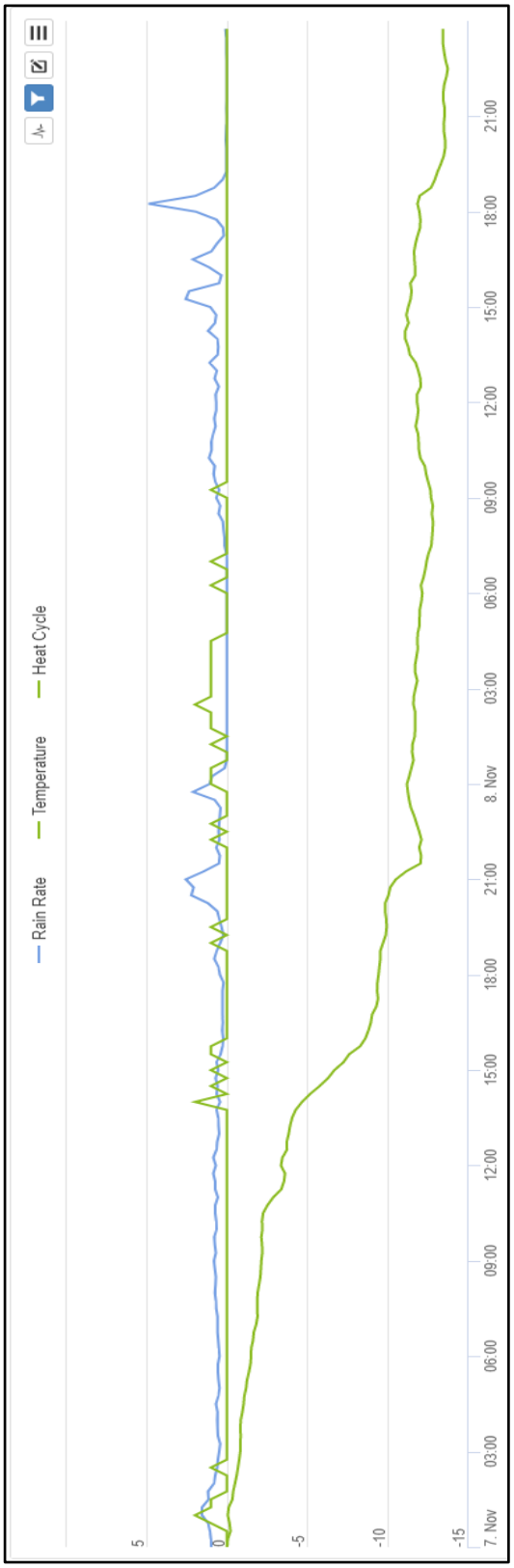


Figure 4.7 **Brian Head precipitation rate (blue), icing cycles (upper, green) and temperature (lower) in the November 7-8 storm period. This graph is focused on a period of significant icing activity from the afternoon of November 7 to the morning of November 8.**

December 2020

December precipitation was again below the average in most areas, except for some areas of central Utah which are near the average. Figure 4.8 shows December precipitation patterns as a percentage of the monthly average.

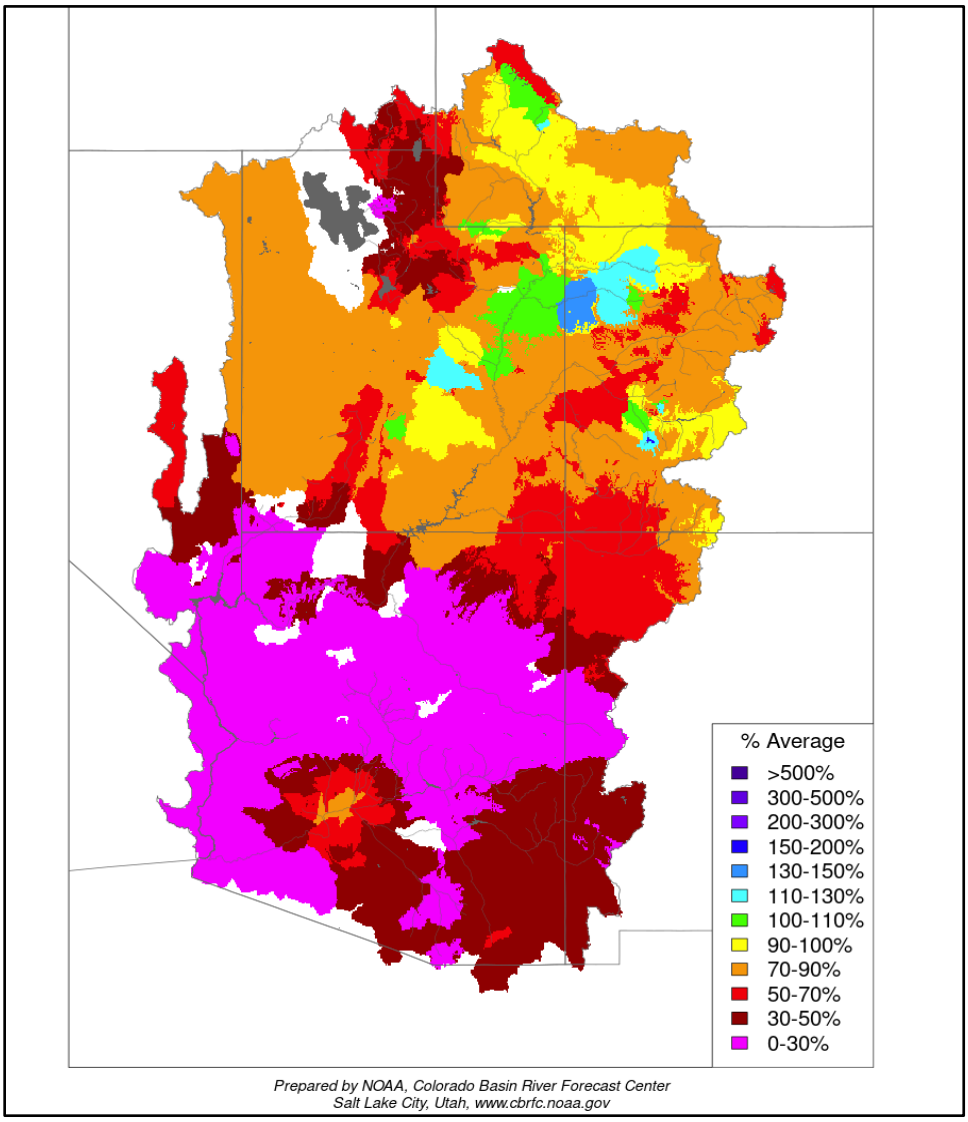


Figure 4.8 **December 2020 precipitation, percent of normal**

After dry weather in early December, a combination of two systems brought a broad band of moisture across Utah on December 12. Temperatures were initially stable in the lower atmosphere and prevented much seeding, although a cold front during the day resulted in 700 mb temperatures cooled to around -12°C and improved vertical mixing. Seeding was conducted throughout the day mainly in southern Utah, but at some sites in central Utah as well. Icing activity was observed at Brian Head through much of the midday period. Snowfall tapered off during the evening and seeding operations were

gradually terminated. Precipitation totals with this system were around 0.5 inch of SWE both in the Brian Head area and along the main spine of the Wasatch Range across central Utah, with much lighter amount at lower elevations.

A disorganized trough on December 14 resulted in light and patchy snowfall initially, along with a stable temperature profile in the lower levels. Seeding operations were initiated at some higher elevation sites near Brian Head, and later expanded to other areas as mixing improved and lower clouds developed across the area. Significant icing was noted at Brian Head in the afternoon and evening, confirming favorability for seeding operations in that area (Figure 4.9). The 700 mb temperature was around -13°C at the site (generally near -10°C at 700 mb) with a northerly wind. By later in the day, a lower cloud deck had developed over much of the area, based around 6,000 feet elevation with a cloud base temperature near -5°C. This made conditions more favorable for operations. As the system exited the area, seeding generally ended overnight except for a few sites in central Utah where strong orographic lifting kept some light snowfall going into the night. All seeding ended by early on December 15. Storm totals were generally light, with 0.1 – 0.2 inches of SWE in most areas with some localized amount to around 0.4 inches.

A strong and well-organized trough moved from California into the Great Basin on December 17th. Strong southerly winds helped to improve mixing, with seeding beginning midday in some areas with a long downwind trajectory over the seeding target region. Widespread seeding was conducted for all portions of the target during the afternoon and evening hours as winds become more westerly, with cooling aloft down to around -7°C by evening and near -8°C overnight. Lower level moisture fields improved during the evening hours, and icing began at Brian Head around 1900 MST and continued intermittently through the night. Seeding operations continued to increase through the evening hours, with more sites added in anticipation of a shift to northwesterly winds overnight. Skies were clearing by the morning of December 8 and seeding operations ended at that point. Precipitation totals were highest in central Utah with as much as 1.3 – 1.4 inches at some sites from Skyline area to east of Richfield, averaging about an inch of water through this portion of the target area overall. Eastern Tooele County averaged around 0.5 inch of water equivalent and the southern mountains (including Brian Head area) generally around a quarter inch.

A closed low moved onshore in southern California early on December 28th, tracking eastward to the Arizona border by late in the day. This system brought light snowfall to southern Utah from a higher cloud deck initially, unfavorable for seeding. Temperatures remained cold at lower elevations with a stable temperature profile and light northeast winds at lower levels through much of the day. However, by early afternoon a more significant snowfall band arrived and mixed gradually improved in southern Utah, with some sites activated at mid and upper elevations in the Brian Head area. A period of light icing activity was noted at Brian Head in the evening with a site temperature of -12°C, indicative of SLW in the area. Although lower levels remained somewhat stable, seeding operations continued overnight in areas of higher terrain across southern Utah with a 700 mb temperature near -10°C. By the morning of the 29th, moisture exited the state as the main low center weakened and moved eastward across Arizona. Seeding operations ended at that point. Precipitation totals from this system averaged about a half inch in central Utah (although conditions were not favorable for operations there), and generally 0.5 – 1.0 inches in the southern mountains. Locally higher amounts up to 1.3 inches were noted in the Brian Head area.

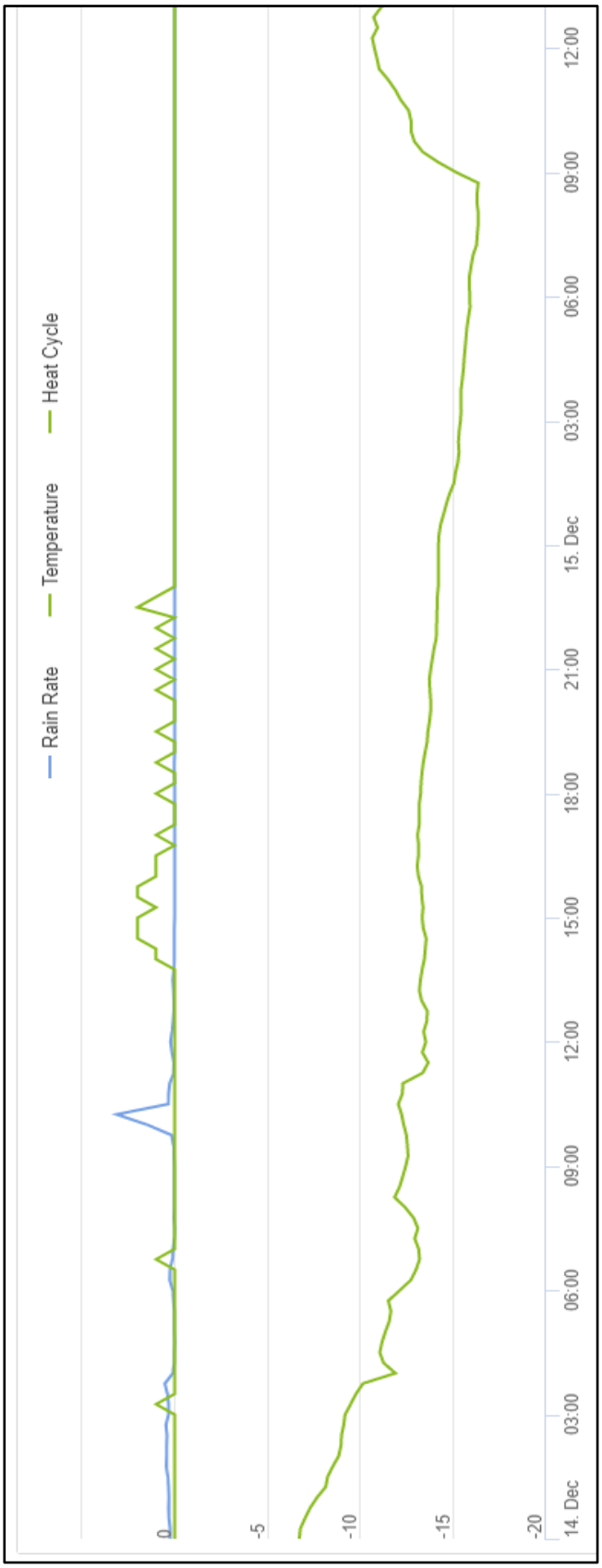


Figure 4.9 **Brian Head precipitation, icing, and temperature for December 14-15**

January 2021

January was another fairly dry month, especially in northern portions of the target areas. Figure 4.10 shows the monthly precipitation as a percentage of normal in January.

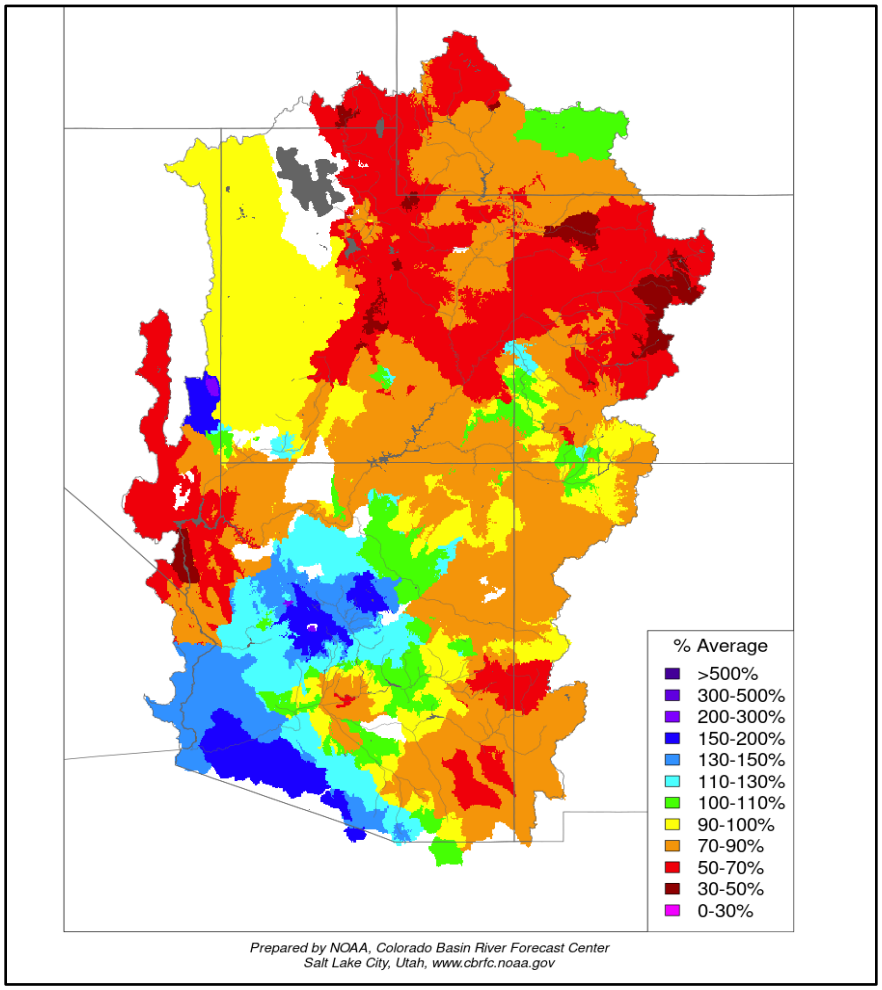


Figure 4.10 January 2021 precipitation, percent of normal

A fast-moving cold front approached Utah late on January 4th, with some lightning upstream over Nevada within the frontal zone. Temperatures over Utah were quite warm ahead of the system, near 0°C at 700 mb but were around -8°C behind the cold front. This cold front affected Tooele County as well as northern portions of the central Utah target areas overnight, with seeding conducted overnight in these areas. By early on the 5th, skies were clearing, and operations were terminated during the morning hours. Precipitation totals ranged from about 0.1 – 0.5 of SWE at SNOTEL sites, with the higher amounts around Sanpete County in central Utah. From Piute County southward, totals were 0.1 inch or less and no seeding was conducted in these more southern areas.

A trough moved southeastward into Utah on the night of January 8-9, with the 700-mb temperature cooling to around -10°C near the center of the trough. Snowfall was somewhat spotty and localized, affecting mainly the west-central and central portions of the state focused on Millard and Sanpete Counties. By morning, snowfall had mostly ended as the system moved southward out of the

area, and seeding ended by mid-morning. Snowfall amounts were light, with mostly 0.1 – 0.2 inches of SWE at the SNOTEL sites.

Lingering moisture in the wake of a closed low that crossed Arizona and New Mexico began to move northward into Utah ahead of another approaching system. This initiated convective activity during the day on January 22nd in southerly flow. The 700 mb temperature was around -5 to -7°C, with shower activity beginning midday in southwestern Utah and expanded into some other areas (mostly southern mountains) during the afternoon hours. Seeding was initiated to focus on areas with somewhat substantial convection, and operations gradually expanded to include most target areas, Tooele County included, through the evening hours. The main trough centered over California kept shower activity going overnight in some areas of Utah. On January 23rd, shower activity remained focused mostly on Tooele County, with the southern half of Utah being essentially dry. Targeting was a challenge due to winds being light and variable in some areas, but seeding continued through the day. A couple sites remained operating the following night (January 23-24) but remained on in a few areas where a lower cloud deck persisted. Dry weather returned and operations ended early on January 24th. Precipitation totals were quite variable due to the showery nature of the precipitation, ranging up to locally 1.5 inches but with most of the target area SNOTEL sites receiving 0.5 – 1.0 inches of SWE.

A vigorous trough developed into a closed low as it moved from southern California into Arizona on January 25th. Due to the closed wind circulation pattern, with the system mainly over Arizona, winds in southern Utah became easterly as precipitation developed there on January 25th. The wind direction limited seeding options for some areas, but was favorable for targeting many southern mountain areas. Precipitation was light initially but increased later in the day, with 700 mb temperatures near -10 to -11°C. By evening, the well-defined, vigorous closed low was centered near the Arizona/Nevada border. A band of moderate to briefly heavy snowfall affected portions of southwestern Utah with winds remaining out of the east to southeast. The Cedar City weather radar indicated the presence of liquid water in this band, favorable for seeding. The main band of snowfall advanced slowly northward and weakened overnight, with winds become lighter and variable. Seeding operations were expanded to include the Pine Valley mountains and also up to about Piute County in southern Utah, with favorable conditions not expected to develop any further north. This became a significant snowfall event for lower elevations of southwestern Utah, with the snow level dropping to 3,000 feet elevation (just above St. George) overnight and reports of 8 inches or more of snowfall in the Pine Valley area. Snowfall had mostly ended by the morning of the 26th and seeding operations were terminated. The 24-hour SWE totals from this system ranged from a half inch or less in central Utah (where conditions were not favorable for seeding) to over an inch in some far southern portions of the state, especially areas south and southeast of Brian Head. Totals of around an inch of water content extended over to the Pine Valley mountains as well.

A trough moved from California into the Great Basin region on January 29th, bringing snowfall to southwestern Utah initially in southerly flow. The 700 mb temperature was around -7°C initially, with favorable seeding conditions developing by late morning in the Brian Head area. Seeding was initiated there by late morning, expanding north and east during the afternoon hours as precipitation spread across the area. Much of the snowfall was from a higher cloud deck, although areas of lower clouds were visible from surface camera images. Precipitation was generally of the stratiform and orographic type, although a few weak convective elements were noted. Precipitation became more showery around Washington County by late afternoon with lower clouds developing, and southwesterly winds favorable for seeding from the lower sites in that area. Conditions continued to improve and seeding operations were expanded

to include Tooele County by evening, with increased convective activity noted across portions of the state. Overnight (January 28-29) winds became westerly with the 700 mb temperature cooling to -8 to -10°C. Precipitation ended late in the evening for far southwestern Utah but snowfall and seeding continued overnight elsewhere. Brian Head reported about 8 inches of snowfall with intermittent icing activity there through the evening hours (Figure 4.11). By the morning of January 30, skies were clearing, and all seeding operations ended. Most precipitation totals from this system were in the 0.3 to 0.6 inch range, with some totals as high as 0.8 to 1.3 inches in the Brian Head area.

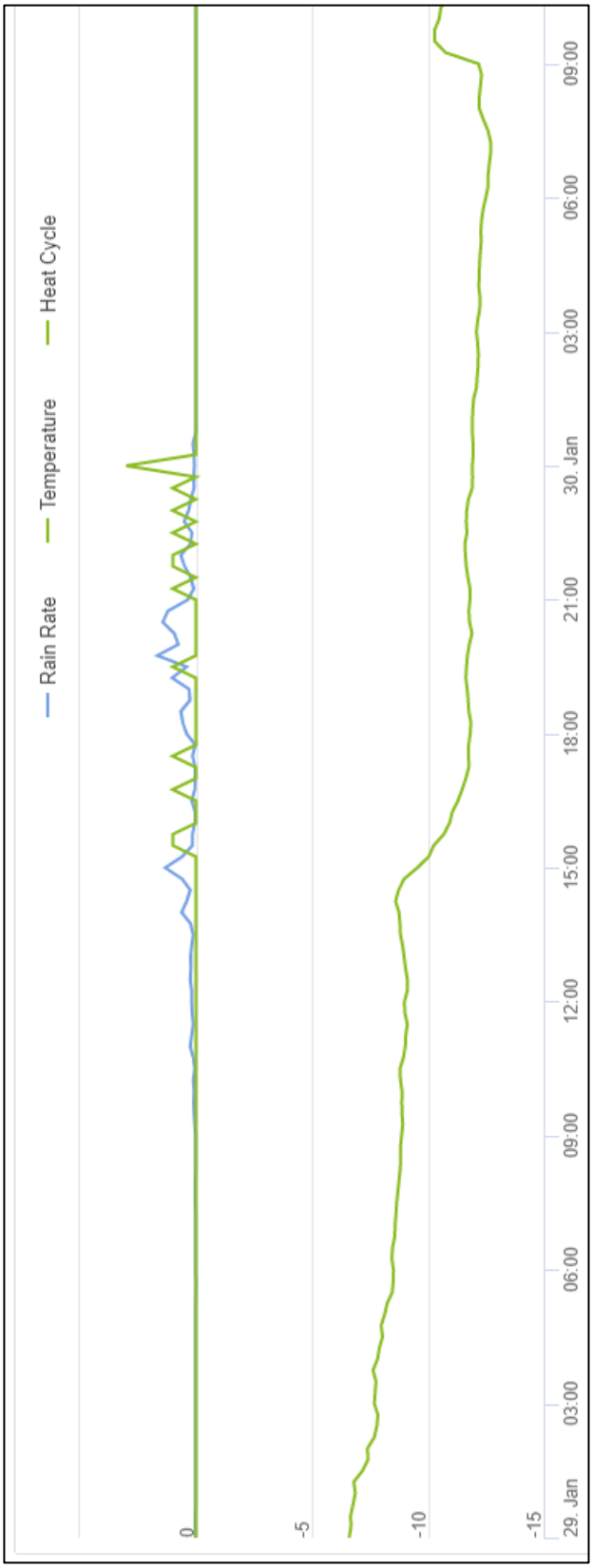


Figure 4.11 **Brian Head precipitation, icing, and temperature for January 29-30**

February 2021

February was an active weather month for portions of the area, with precipitation ranged from somewhat above normal in portions of central Utah to well below normal in the far south. Figure 4.12 shows the February precipitation pattern across the region in comparison to average values.

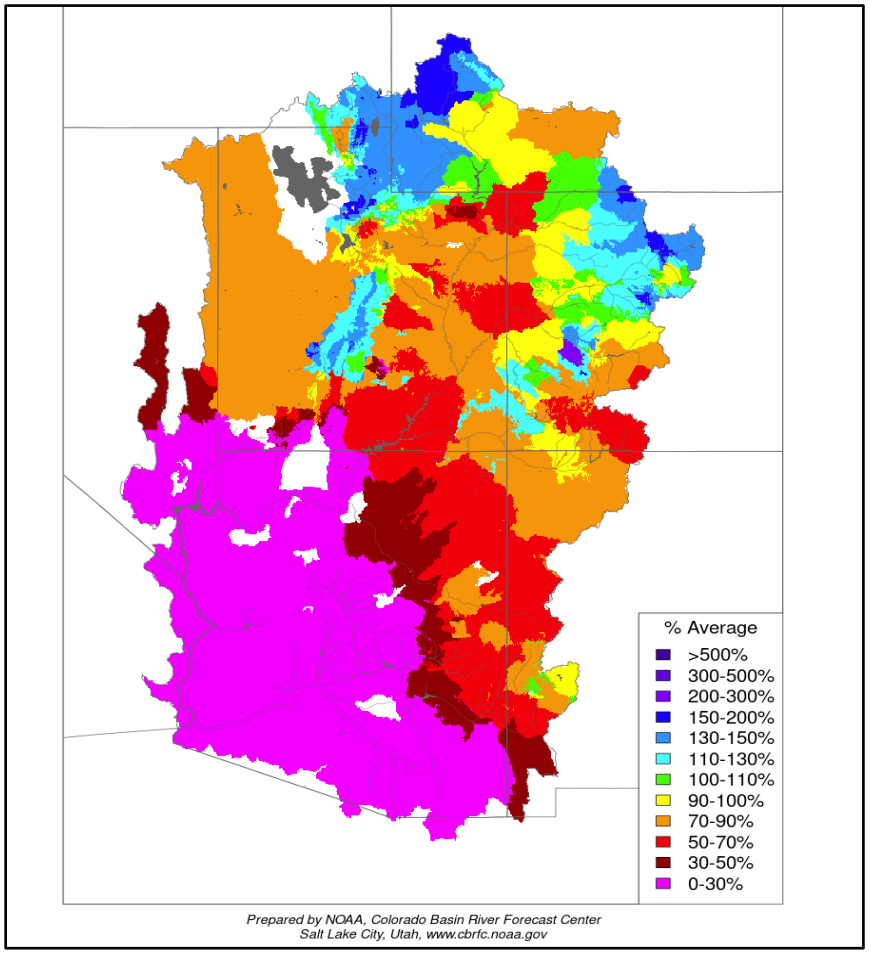


Figure 4.12 February 2021 precipitation, percent of normal

A fast-moving cold front with embedded convective activity affected northern and central portions of Utah on February 3rd. The 700 mb temperature cooled from about -5 to -10° C with the passage of the front, and banded precipitation features developed that contained convection and even lightning activity in some areas. Seeding began early in Tooele County and expanded into central Utah target areas during the morning and midday hours. By mid to late afternoon, the cold front has moved down to about Piute County with seeding operations from that area northward. For southern Utah, precipitation activity later in the day was very short-lived and operations were not expanded any further south. As the cold front moved away from the area, forecast models showed very light orographic precipitation in central Utah overnight (February 3-4), and limited seeding operations continued there although most ended late evening. The 700 mb temperature cooled to about -12°C overnight. Snowfall had generally ended by the morning of the 4th although some orographic clouds persisted in central Utah and seeding continue locally

until mid-morning. Precipitation totals ranged from about 0.1 to 0.5 inches of SWE in seeded portions of the target areas with this system, with some locally higher totals in central Utah.

A fast-moving trough tracked across northern and eastern portions of Utah on February 5th. A weak warm advection pattern resulted in the 700 mb temperature warming from about -10 to -8° C during the day. By mid-afternoon, lower levels had moistened enough for seeding operations in Tooele County and portions of central Utah. Good orographic lifting in the strong flow perpendicular to mountain barriers was the most favorable characteristic of this system, with northern portions of central Utah having a good orographic snowfall scenario. By later in the evening, snowfall decreased as the system moved out of the area, with partial clearing overnight and seeding ops ending late evening. Precipitation totals ranged from 0.1 to 0.4 inch SWE in Tooele County and central Utah with this event.

A trough extending from California across Utah on February 12th brought a good amount of low-level moisture, although temperatures were relatively warm, and precipitation was scattered and disorganized. Brian Head had intermittent precipitation and icing activity with a site temperature of -6°C (700 mb temperature was near -4°C), illustrated in Figure 4.13. Winds were fairly light, and due to marginal conditions, only a couple of seeding sites in the Brian Head area were activated in the morning. Precipitation ended by around midday, however and seeding was terminated. Precipitation totals with this system were mostly 0.2 – 0.5 inches.

A trough extended from Oregon into northern Arizona on the morning of February 13th. Widespread precipitation was occurring over Utah in a south-southwesterly wind pattern, with the 700 mb temperature near -5 to -6°C. As the trough core approached, cooling aloft resulted in improved cloud types for seeding operation, with more orographic and convective activity. Seeding operations began midday in southwestern Utah, expanding into more of western and central Utah during the afternoon as winds shifted from southerly to westerly and temperatures cooled aloft. Some lower clouds with good liquid water content were observed visually and in radar data. By evening, winds shifted to the northwest and the 700 mb temperature cooled to around -10°C with widespread seeding conducted for all target areas. This continued overnight with almost due northerly winds behind the trough axis, with the trough moving to the east and south by early February 14th. However, a lower cloud deck remained in place in some areas on the 14th and seeding operations continued into the morning hours at some locations. Precipitation totals were significant from this moist storm system, ranging from about 0.7 to 2.0 inches at most target area SNOTEL sites.

A large, cold and moist low pressure trough moved from the Pacific Northwest into the northern and central Rockies states during the February 15-17 period. This resulted in a prolonged cold advection pattern in mostly northwesterly flow, with good moisture and widespread convective activity that included some occasional thunderstorms. The focus of most of this activity was in northern and central Utah, although occasional precipitation affected southern Utah as well. The 700 mb temperature was generally from -10 to -12°C during this period, with visual, satellite, radar and other observations suggesting good amounts of liquid water in a situation that looked to be ideal for cloud seeding. Operations were conducted in Tooele County and western and central Utah, likely affecting downwind areas further south as well, beginning the night of February 15-16 and continuing until midafternoon on the 17th. Tooele County experienced some lake enhanced snowfall at times, downwind of the Great Salt Lake. The 48-hour SWE totals at SNOTEL sites ranged over three inches in Tooele County, to 1-2 inches in central Utah mountains and lesser amounts in the south.

A cold front crossed Utah from northwest to southeast on February 20th, with the 700 mb temperature falling from -5°C ahead of the front to -10°C or colder behind it. This system brought snow showers to portions of central and southwest Utah during the afternoon and early evening, with some limited seeding opportunity. Precipitation totals ranged from about 0.1 to 0.4 inches, with snow showers ending during the evening hours.

A cold, dry trough of low pressure affected Utah on February 24th. Only a small area of central Utah had enough moisture to attempt seeding operations, near the border area of Piute and Wayne County during the late afternoon and early evening hours. There were some weak convective snow showers and several sites ran in that area for a few hours, with about 0.1 inch of SWE in that local area.

A cold air mass with limited moisture, combined with daytime heating to produce some convective snow showers during the afternoon hours in portions of the state. The 700 mb temperature was near -13 to -15°C, with seeding conducted with convective snow showers from about 1230 to 1800 MST. Some isolated lightning activity was observed. Seeding ended in the evening as showers dissipated with sunset. Precipitation totals ranged from about 0.2 – 0.5 inches in seeded portions of the target areas.

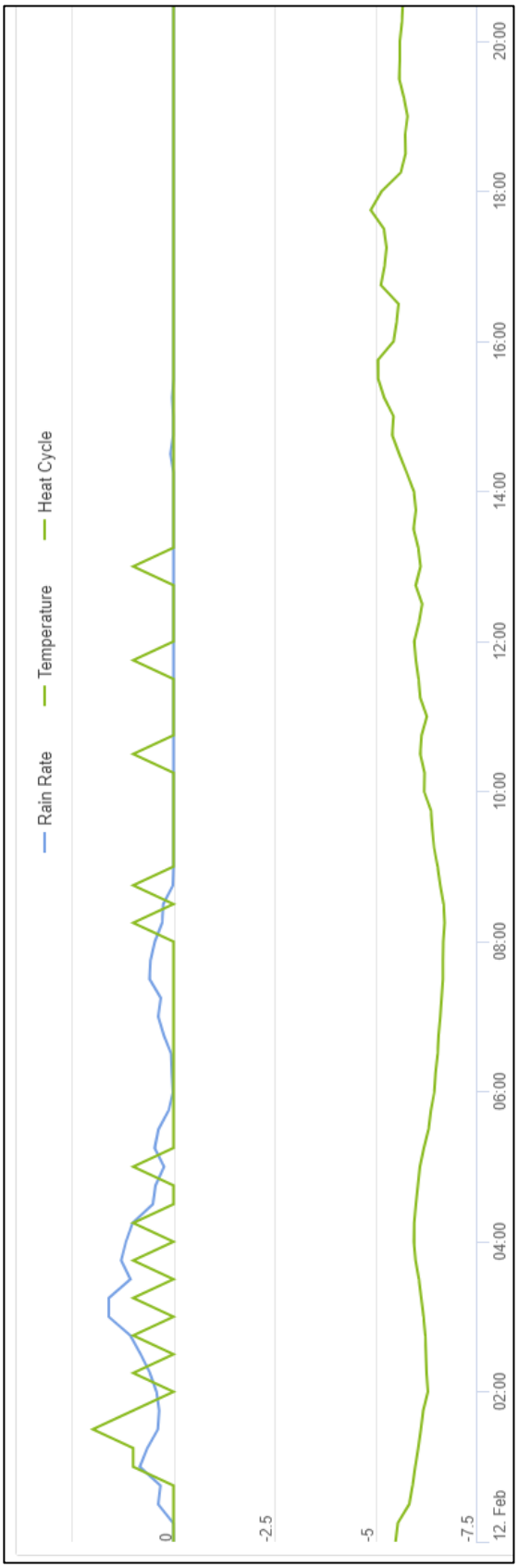


Figure 4.13 **Brian Head precipitation, icing, and temperature for February 12**

March 2021

March presented somewhat of a contrast in precipitation patterns around the state, although most of central and southern Utah was again below average. Figure 14 shows monthly precipitation as a percentage of normal for March.

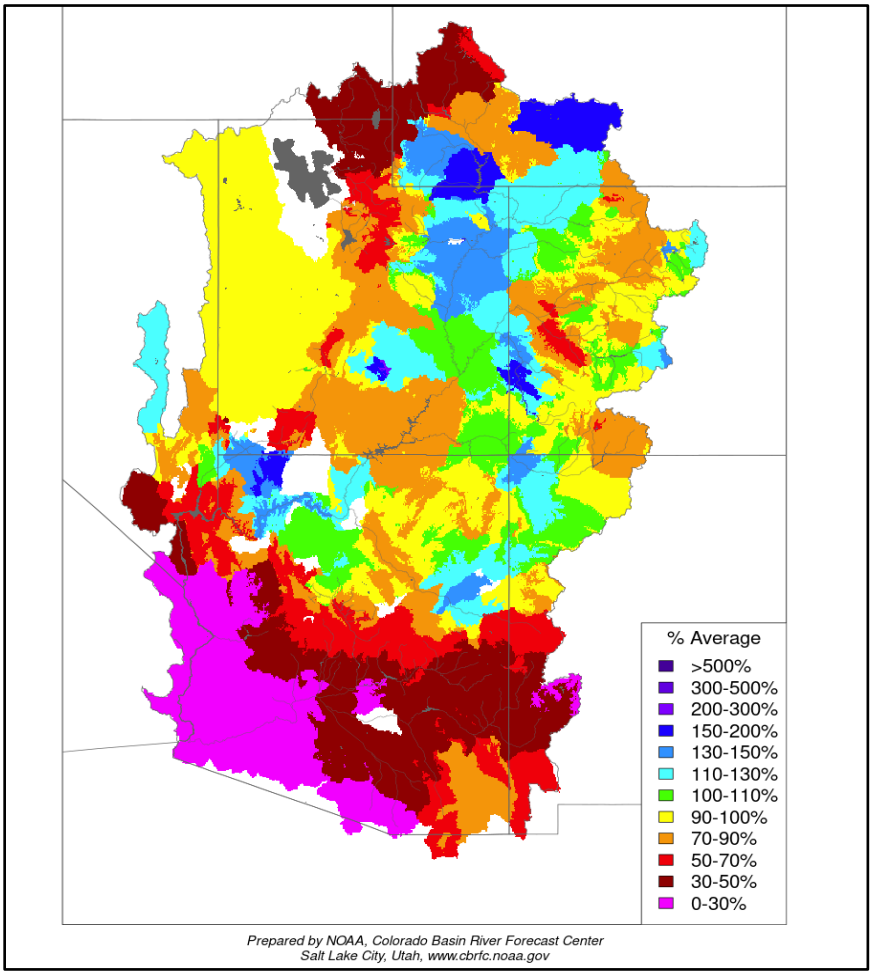


Figure 4.14 March 2021 precipitation, percent of normal

A strong closed low moved onshore in southern California on March 3rd, and quickly northeastward toward Utah. The lower level air mass was very dry and conditions were quite windy with the arrival of this system, but there were some radar indications of cloud SLW aloft and seeding began late in the evening. The 700 mb temperature fell to around -6°C overnight and winds were from the southeast initially, shifting to the southwest by early on March 4. Seeding was conducted overnight, then adjusted on the morning of the 4th as winds shifted to the northwest and light precipitation continued. By midday on the 4th, precipitation and seeding operations ended, with totals mostly between 0.2 – 0.5 inches and confined to the southern mountains with this event.

A cold trough centered just off the California coast on March 10 slowly worked its way into the Great Basin on March 11. Moisture over Utah was quite limited in southerly flow, but convective activity gradually increased with showers developing from southwest to northeast across the state. Seeding

was initiated in the Brian Head area on the afternoon of the 10th, and expanded across southern Utah during the evening hours. A similar pattern continued on the 11th, with the 700 mb temperature remaining near -10°C and scattered convective snow showers developing with slightly better (although still very limited) moisture. Seeding operations continued mainly in southern Utah, where coverage of showers was the best, but also in Tooele County for a time. Seeding ended on the evening of March 11 as convective shower activity diminished by about sunset. Precipitation during this event was somewhat spotty, but generally ranged from 0.3 to around 1.0 inches in the target areas.

The same cold trough of low pressure responsible for the March 10-11 shower activity moved slowly eastward across the southwestern U.S. on March 12-13, bringing additional seeding opportunity to the southern mountains. Significant snowfall was already occurring in Washington County early on March 12, with the snow level near 2,500 feet and a mix of rain and snow even in St. George. Winds were generally easterly in the mid-levels with some northerly component in the lower levels, given the location of the low centered near Las Vegas. This made targeting seeding material somewhat challenging, but favorable locations were activated to target the southern mountains as covering of snowfall increased during the day. The 700 mb temperature was generally near -10°C. By the evening of the 12th, snowfall activity became concentrated near a fairly localized circulation center near Beaver and Iron counties, with activity tapering off elsewhere. Given this and the existing wind patterns, seeding operations were terminated except at one site (Pine Valley) which continued overnight and into the morning of the 13th. The circulation center in western Utah moved slowly southward and again produced snowfall for some lower elevations of Iron and Washington counties on the night of March 12-13. On the 13th, snowfall generally ended and no additional seeding was initiated. Precipitation totals during this event were again quite variable, but generally between 0.3 – 0.7 inches in the southern Utah mountains.

As of March 15th, the core program ended for the season, with the total budgeted amount of seeding for this program having also been used. There were another five seeded storm events in March for the Lower Basin States funded extension period, as the weather pattern was fairly active during this period.

Another closed low moved into Arizona on March 15-16, with southern Utah receiving scattered snow shower activity. Seeding was initiated for the southern mountains on the evening of March 15 and continued through the daytime and into the early evening of the 16th. Winds were generally from a northeasterly direction with 700-mb temperatures around -5 to -6°C. Fairly consistent icing activity was observed at the Brian Head site through the day on the 16th, as seen in Figure 4.15. Skies cleared by the night of the 16th as the low moved out of the area. Precipitation totals in the southern mountains ranged from about 0.2 to 0.7 inches of SWE with this system.

A large trough brought an extensive frontal boundary into Utah on March 20, with precipitation spreading from north to south through the state. The 700 mb temperature dropped from above -5° C ahead of the system to around -10° C behind the cold front. Seeding was initiated in central Utah portions of the extension areas during the afternoon, with some brief activity into southwestern Utah later in the day although staying generally over the northern half of the area. Seeding operations continued overnight from Piute County northward as snow shower activity continued behind the cold front in a northwesterly wind pattern. Snow showers and seeding activity ended early on March 21, but some snow showers re-developed in central Utah around Sanpete County during the afternoon hours and some additional seeding was conducted there in a north-northwesterly wind pattern. All seeding ended on the evening

of March 21 with clearing skies. Totals from this storm period ranged from 0.3 to a little over an inch in central Utah, and mostly under 0.3 inches in the south.

A trough moved southeastward through the Great Basin on March 22 and developed a closed circulation center near northwestern Arizona by the morning of March 23. A cold and moist air mass over Utah, combined with daytime heating, resulted in scattered convective snow showers in a northeasterly wind pattern on March 23. Despite the cold air mass, with a 700 mb temperature around -10° to -11° C in most areas, some of these showers contained significant SLW and even some lightning in a few portions of central Utah. Seeding was conducted from midday into the evening hours at a couple of sites near the Boulder Mountain area that were favorable for this wind pattern. Precipitation totals were generally 0.1 – 0.2 inches at SNOTEL sites.

A trough moved across Utah on March 26th, with some convective snow shower activity developing in northwesterly flow behind the trough axis following an earlier period of light snowfall from a high cloud deck. Snow showers were widely scattered and fairly light, although some seeding was conducted from late morning into the afternoon hours. Storm totals ranged generally from 0.3 to 0.7 inches in central Utah and 0.1 – 0.4 in the southern mountains, although only a portion of this was determined to have any seeding potential. Seeding operations in this event also included some hours for the three-county extension in central Utah that was initiated late in the season.

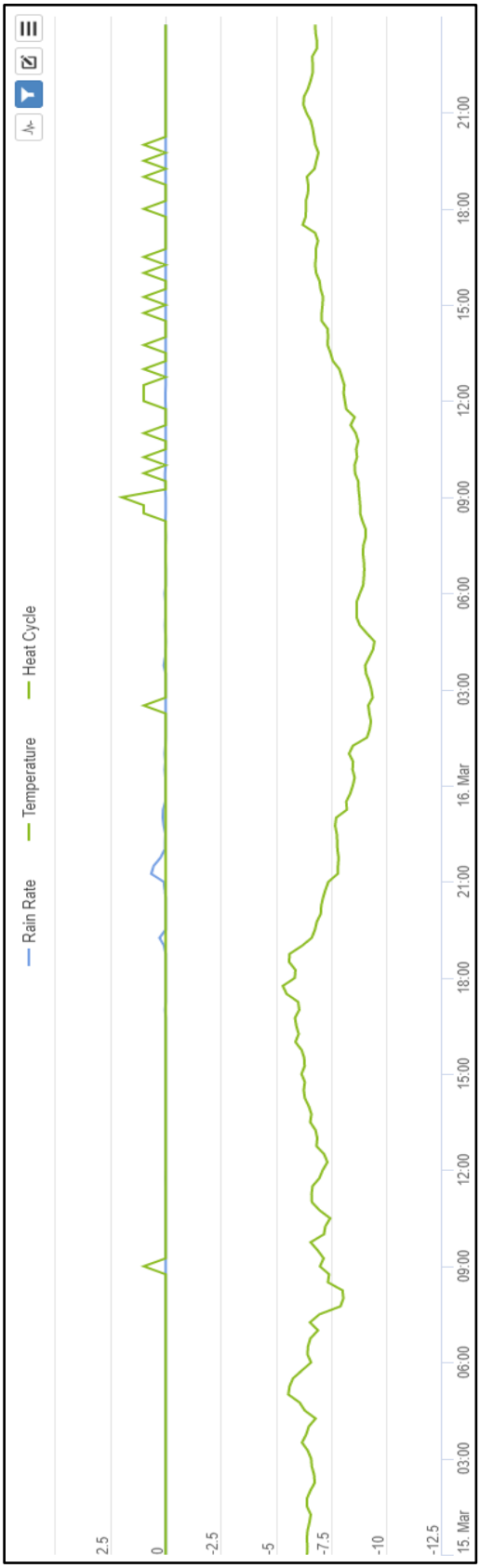


Figure 4.15 **Brian Head precipitation, icing, and temperature on March 15-16, 2021**

April 2021

April, as most months this season, again brought below normal precipitation to the target areas. Figure 4.16 shows precipitation patterns in April. There were, however, five additional seeded periods during the month, including three for the three-county extension area after April 15th.

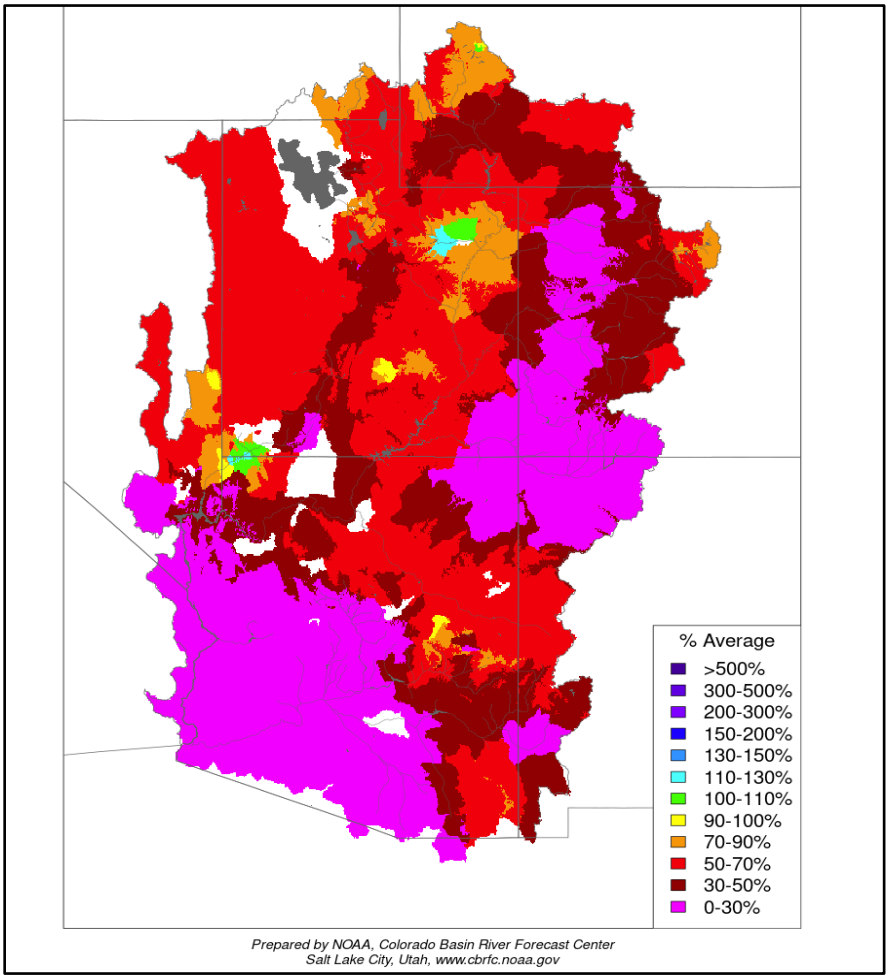


Figure 4.16 April 2021 precipitation, percent of normal

A large trough was centered over the Great Basin on April 14th. Despite 700 mb temperature being a little on the warm side, development of convective showers and a few thundershowers over central Utah during the afternoon made conditions favorable for seeding in that area. Seeding was conducted from about 1400 – 1900 MDT mainly around Sanpete County. SNOTEL SWE totals were generally in the 0.1 to 0.3 inch range, although these may have been reduced by some melting.

On April 15th, a large trough remained over Utah with somewhat more favorable conditions for seeding due to colder temperatures and more moisture in the lower levels than on the 14th. The 700 mb temperature was around -5 to -7°C in northwesterly flow. Cooling temperatures during the April 14 – 15 period were accompanied by a few icing cycles at Brian Head during the overnight hours (Figure 4.17). Convective snow showers developed once again with daytime heating, and seeding was conducted for the Lower Basin Extension areas from mid-morning until the evening hours, as well as a couple of sites for

the three-county extension area in central Utah. SNOTEL SWE totals of up to around 0.5 inches were observed, although may have been locally higher than this.

With only the three-county extension area in central Utah remining active, seeding was once again conducted in that area with a light northeasterly wind pattern as convective snow showers once again developed during the daytime hours. This was in association with the same closed low remaining in the area, and 700 mb temperatures near -6 to -8°C in this area. Seeding was conducted from midday into the evening hours, ending around sunset as shower activity dissipated. Precipitation (SWE) totals in this portion of central Utah were in the 0.2 to 0.5 inch range.

Moisture increased in a slow-moving frontal zone over Utah on April 26, with the core of the trough centered over northern Nevada. Seeding was conduced for the three-county extension area of central Utah during the afternoon and evening, with significant precipitation there and the 700 mb temperature near -5°C. Seeding operations ended late in the evening as precipitation diminished. SNOTEL data showed SWE total from 0.6 to 1.5 inches in central Utah with this system, although some of this was in the warmer portion before seeding operations began.

A complex low pressure trough remained over Utah on April 27th, with a 700 mb temperature near -3 to -4° C. Multiple circulation centers around the state complicated the wind patterns, but central Utah was mostly in a light northerly wind pattern with good lower level moisture that fueled the development of convective snow showers during the day. Seeding was conducted from the late morning through the early evening hours for the three-county extension area. Precipitation totals were mostly in the 0.2 to 0.3 inch range at SNOTEL sites in this area. This was the final seeded event of the season.

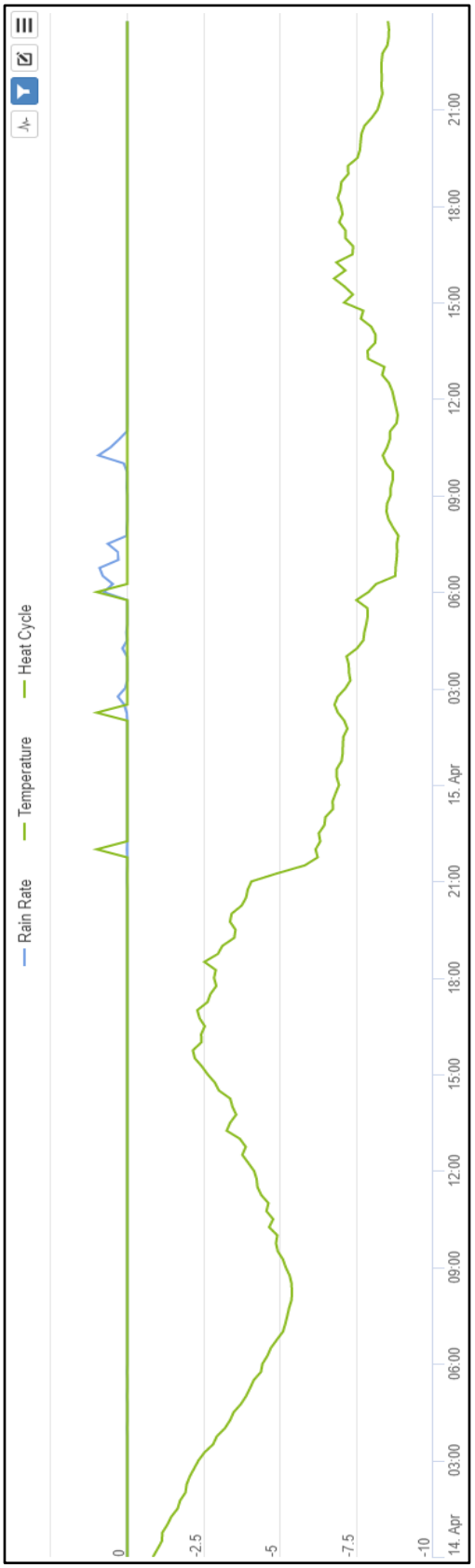


Figure 4.17 **Brian Head precipitation, icing, and temperature for April 14-15, 2021.**

5.0 ASSESSMENTS OF SEEDING EFFECTS

5.1 Background

The seemingly simple issue of determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program is often a rather difficult task, however, and the results, especially single-season indications, should be viewed with appropriate caution. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area. The ability to detect a seeding effect becomes a function of the size of the seeding increase relative to the natural variability in the precipitation pattern. Larger seeding effects can be detected more readily, and with a smaller number of seeded cases than are required to detect smaller increases.

Historically, in weather modification, the most significant seeding results have been observed in wintertime seeding programs for snowpack augmentation in mountainous areas. The apparent increases due to seeding are generally less than 20% for individual seasons, and in the range of 5-15% for the long-term average. This section of the report summarizes statistical evaluations of the effects of the cloud seeding on the precipitation and snowpack within the higher elevations of this program's targeted areas. When expressed as percentages, the increases may not initially appear to be particularly high. However, when considering that these increases are area-wide averages covering thousands of square miles, the volume of the increased runoff is impressive.

NAWC has used a commonly employed evaluation technique since this seeding project was first evaluated following the 1978 water year. This technique, referred to as the target and control comparison, is based on evaluating the effects of seeding on a variable that would be affected by seeding (such as precipitation or snow water content). Records of the variable to be evaluated are acquired for an historical (non-seeded) period of sufficient duration, ideally 20 years or more. These records are partitioned into those that lie within the designated seeded target area of the project and those in appropriate control areas. Ideally the control sites are well-correlated with the target area sites but would be unaffected by the seeding. All the historical data, e.g., precipitation, in both the target and control areas are taken from a period that has not been subject to cloud seeding activities, since past seeding could affect the development of a relationship between the target and control areas. These two sets of data are analyzed mathematically to develop a regression equation which estimates (calculates) the most probable amount of natural target area precipitation, based on the amount of precipitation observed in the control area. This equation is then used during the seeded period to estimate what the target area precipitation should have been in the absence of cloud seeding. A comparison can then be made between the estimated natural target area precipitation and that which occurred during the seeded seasonal periods.

This target and control technique works well where a good statistical correlation can be found between the target and control area variables. Generally, the closer the control sites are to the seeding target area, the higher the correlation will be. Control sites which are too close to the target area, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, correlations of 0.90 or better are considered excellent and correlations around 0.85 are good. A correlation of 0.90 indicates that over 80

percent of the variance (random variability) in the historical data set is explained by the regression equation. Correlations less than about 0.80 are still acceptable, but it would likely take much longer (many more years of comparison) to attach any statistical significance to the apparent seeding results.

5.2 Evaluation Approach

With the establishment of the Natural Resources Conservation Service's (NRCS) SNOTEL automated data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before the automated system was developed, these data had to be acquired by having NRCS personnel visit the site to make measurements. This is still done at some sites. Historically, Utah has had snowpack measurements taken at monthly intervals for many years and unlike many other states, precipitation measurements are available from some of these same high elevation sites. Precipitation and snowpack data used in the analysis were obtained from the NRCS and/or from the National Climatic Data Center. The current season NRCS data are considered provisional and subject to quality control analysis by the NRCS.

There have been, and continue to be, multiple cloud seeding programs conducted in the Utah and some surrounding states. As a consequence, potential control areas that are unaffected by cloud seeding are somewhat limited. This is complicated by the fact that the best correlated control sites are generally those closest to the target area, and most measurement sites in this part of the state have been subjected to contamination at some time by numerous historical and current seeding programs. This renders such sites of questionable value for use as control sites. The potential effects of other cloud seeding projects beyond (downwind) their intended target areas is a consideration especially when selecting control sites. Some earlier weather modification research programs have indicated that the precipitation can be affected in areas downwind of the intended target areas. Analyses of some of these programs have indicated increases in precipitation in these downwind areas out to distances of 50-100 miles. Thus, control sites for evaluation of the southern and central Utah seeding program are located in areas that are not expected to be significantly affected by any current or historical seeding operations.

Our normal approach in selecting control sites for a new project includes looking for sites that will geographically bracket the intended target area. The reason for this approach is that we have observed that some winter seasons are dominated by a particular upper airflow pattern while other seasons are dominated by other flow patterns. These different upper airflow patterns and resultant storm tracks often result in heavier precipitation in one area versus the other. For example, a strong El Nino pattern may favor the production of heavy winter precipitation in the southwestern United States while a strong La Nina pattern may favor the production of below normal precipitation in the southwest. Having control sites either side of the target area relative to the generalized flow pattern can improve the estimation of natural target area precipitation under these variable upper airflow pattern situations.

Another consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control site may be rejected due to poor data quality, which usually manifests itself in terms of missing data. Fortunately, missing data (typically on a daily basis) are noted in the historical data base so that sites can be excluded from consideration if they have much missing data. We normally eliminate a site if it has significant amounts of missing data. If a significant measurement site move (more than a mile or change in elevation of 100-200 feet) is indicated in the station records, this may also be a factor. The double-mass plot, an engineering tool, will indicate any systematic changes in relationships between the two stations. If changes (shown as

inflections in the slope of the line connecting the points) are significant, a site or sites may be excluded from further consideration.

Using the target-control comparison described above, the mathematical relationships for two variables (precipitation and snow water equivalent, or SWE) were determined between a group of sites in an unseeded area (the control group) and the sites in the seeded area (the target group). From these data, regression equations were developed whereby the amount of precipitation or SWE observed in the unseeded (control) area was used to estimate the amount of natural precipitation in the seeded (target) area. This estimated value is the amount of precipitation or SWE that would be expected in the target area without seeding. The difference between the estimated amount and the observed amount in the target area is the excess, which may be the result of the seeding. Statistical tests have shown that such increases have very little statistical significance for an individual season, and usually fall within one standard deviation of the natural variability. However, an excess obtained by averaging the results of several seeded seasons is much more meaningful.

5.3 Evaluation of Precipitation in the Target Area

In past years several target areas have been evaluated to assess the efficacy of cloud seeding, by examining the precipitation observed at the gauges within the seeded targets. For the current water year, two target areas (see Figure 1.1) were again evaluated. An attempt has been made to consistently utilize the same groups of target and control sites from one season to the next, although there have been a few changes over the years as some sites were discontinued. The following describes the techniques that were used in selection of the target and control sites.

Precipitation Target Sites

The northernmost seeded target in the Central/Southern program is the East Tooele Target (ETT). That area contains the mountain watersheds of the Stansbury and Oquirrh Mountains, located in the eastern portions of Tooele County, south of the Great Salt Lake. Due to the scarcity of available target sites, this target group also includes a valley-level precipitation gauge (Tooele, just over 5,000 feet MSL), as well as a site (Vernon Creek) somewhat south of the official target areas. The locations of the three remaining precipitation gauges that were used in the evaluation for this target are listed in the target area portion of Appendix C and shown in Figure 5.1. The three target SNOTEL gauges are located in the Stansbury and Oquirrh Mountain ranges. The average elevation of the target gauges is 7,157 feet, MSL. Additional high elevation sites in the Stansbury and Oquirrh Mountain Ranges would be desirable in order to provide a more accurate evaluation of seeding effects in these target areas.

The Primary 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 consists of SNOTEL storage gauges. These sites are shown in Figure 5.2. 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.

Precipitation Control Areas

The control site array for the precipitation evaluation of the Eastern Tooele Target seeding operation was the same group of control sites used in recent seasons' evaluations. The control group

consists of six gauge sites, listed in Appendix C and shown in Figure 5.1. Four sites are located in eastern Nevada and two in northern Utah.

The precipitation evaluation control sites used for the Primary Target (PT) area evaluation are located in eastern Nevada and north central Arizona (bracketing the PT area on the northwest and southeast). The locations of these sites are shown in Figure 5.2.

Most of the sites in the control area are NRCS SNOTEL gauges at mountain locations, although in the case of the primary target area of southern/central Utah, other gage sites significantly help the control versus target correlation. These sites have generally remained the same for a significant number of years, except for any necessary changes due to discontinued sites or poor data quality. Elimination or replacement of some lower elevation (non-SNOTEL) co-op sites has been necessary in some cases, and in the past a few data estimates for individual co-op sites have been necessary to fill in small data gaps. This season, two existing control sites of this type, Caliente and McGill in eastern Nevada, did not have data available. A number of possibilities were examined, included simply dropping these sites and producing a new regression equation, or replacing them with other sites in eastern Nevada or western Utah, upwind of the target areas. However, most of the lower elevations sites correlate poorly to the much wetter seeding target areas, and all options explored for a revised control set resulted in lower correlation of the control/target set and a substantially higher year to year variability of the evaluation results. Because of this situation, data estimates were produced for these two control sites for this season based on data from the nearest available sites of similar type. This allows the control set that has been used previously to stay in use for the time being in this particular target/control evaluation. The Tooele County precipitation evaluation, and all those based on snowpack, have different control sets and so are unaffected by the missing data at these two sites.

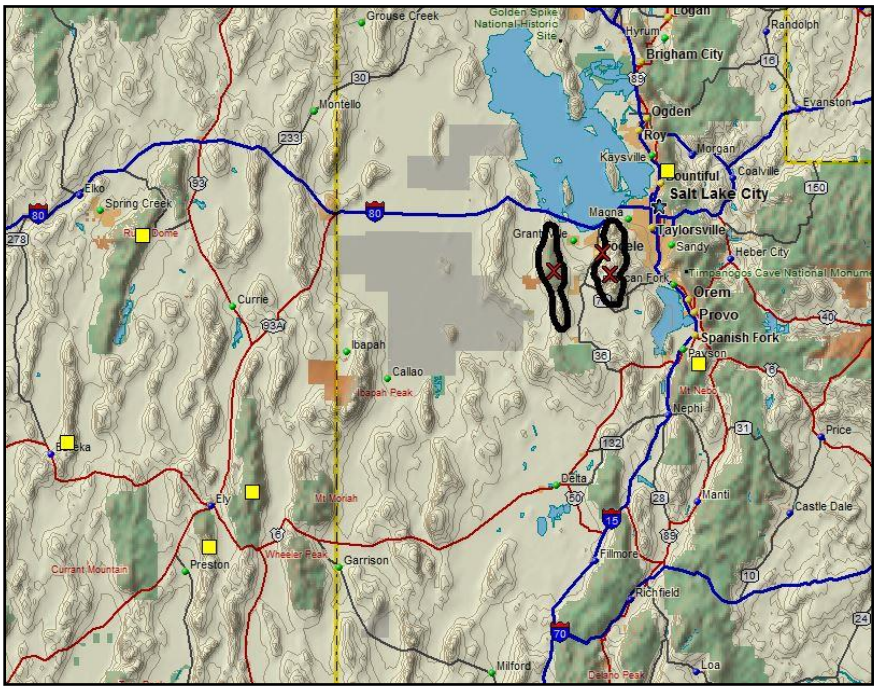


Figure 5.1 **Precipitation sites for Eastern Tooele target/control evaluation; control sites are depicted as squares and target sites with an X.**

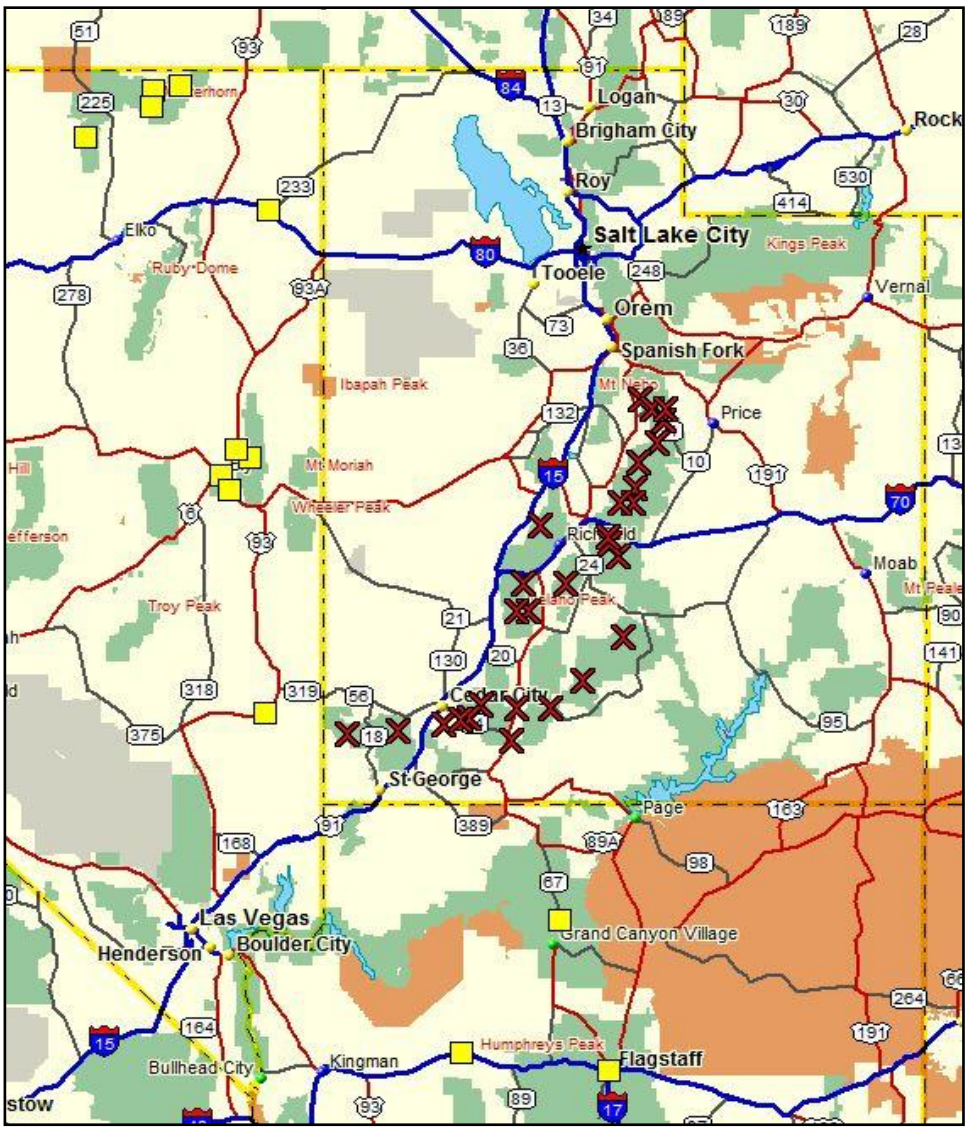


Figure 5.2 **Precipitation target (X) and control (square) sites, primary target area.**

Precipitation Data Compilation

The evaluation was conducted for the December through March period, which represents the period during which operational cloud seeding has been conducted in nearly all the seeded water years, although in a few historical years the latter half of March has not been seeded. Precipitation data for some of the higher elevation target sites were obtained from storage gauge sites. Observations were taken at approximately monthly intervals before the conversion to the NRCS SNOTEL technology, which (at most sites) occurred in the early 1980's. With the advent of the NRCS SNOTEL system, data are available on a daily and even hourly basis, which eliminates some of the timing problems in the earlier data sets. Precipitation amounts for the December-March period were summed for each station, in the two target areas and their respective control areas. Averages were calculated for each of the groups for each individual four-month (December-March) season. The four-month averages for the historical (unseeded) seasons were then used to develop a linear regression equation for the target, which was in turn used to estimate the target area natural precipitation for the seeded period.

In the ETT, the historical (non-seeded) base period includes 28 non-seeded seasons (1957-75, 1983-88, and 1993-95). Seeded years in the ETT target include water years 1976-1982, 1989-1992, and 1996-2020 (36 seeded seasons). A reasonably good correlation between the control and target stations was established, with a correlation coefficient (r value) of 0.78. Target and control sites are listed in Appendix C. The control area sites are shown schematically on Figure 4.1 relative to the East Tooele Target area. Their average elevation is 8,348 feet MSL.

The historical period in the PT consists of an 18-year period (1957-73, and 1984). Seeded years began in 1974 in the PT and continued through 1983. Although seeding resumed in the southern portion of the PT in 1985, it was not until 1988 that a majority of the PT was being seeded again. Therefore, the 1985-87 period has been excluded from the evaluation, with target-wide seeding resuming in 1988 and continuing through the current water year. This provides a total of over 40 seeded seasons for evaluation. The regression analysis between the 12-site control area and the 25-site target area for the 18-year historical period (December-March, 1957-73, 1984 water years) provided an excellent correlation between the two groups. The correlation coefficient (r) is 0.96. This is a very strong correlation and should provide an accurate assessment of predicted natural precipitation in the target area during seeded seasons. The sites that make up the control and target areas are listed in Appendix C. The control area sites (denoted by squares) are shown schematically on Figure 4.2 relative to the Primary Target area. Their average elevation is 7,032 feet MSL.

The linear regression equation developed from the historical relationship between the control and target groups is of the following form:

$$Y_C = A(X_O) + B$$

where Y_C is the calculated average target area precipitation (inches) for a specific period (e.g., December-March), and X_O is the control average observed precipitation for the same period. The coefficients A and B, the slope and y intercept values from the historic regression equation are constants.

The seeding effect (SE) can be expressed as the ratio (R) of the average observed target precipitation to the average calculated (estimated) natural target precipitation, such that:

$$SE = R = (Y_O)/(Y_C)$$

where Y_O is the target area average observed precipitation (inches) and Y_C is the target area average calculated precipitation (inches).

The seeding effect can also be expressed as a percent excess (or deficit) of the expected precipitation in the form:

$$SE = (Y_O – Y_C) / (Y_C \times 100)$$

The regression equations and the historical correlation coefficients for the two target areas are presented in Table 5-1. The stations which constitute each control/target group are listed in Appendix C.

Results of Precipitation Analyses

Table 5-2 provides the ratios of the observed average target area December-March precipitation to the calculated (from the regression equation described above) for the two target areas. A ratio equal to 1.0 would indicate no difference between the observed and predicted precipitation amounts. The difference between these values is also provided to show the average difference (inches) in precipitation during the seeded periods. Tables 5-3a and 5-3b list the results for each seeded season for the Eastern Tooele Target Area and Primary Target Area, respectively.

Table 5-1
Correlation coefficients, variances, and regression equations for precipitation evaluations

Target Group	Equation	Correlation Coefficient (r)	Variance (r^2)
Eastern Tooele (ETT)	$Y_C = 0.88(X_6) – 0.69$	0.78	0.61
Primary Target (PT)	$Y_C = 1.69(X_{12}) – 3.17$	0.96	0.91

Where:

Y_C = Average calculated precipitation for target (December - March)

X_6 = Average two state (NV/UT) control area observed precipitation for December - March for 6 sites

X_{12} = Average two state (AZ/NV) control area observed precipitation for December - March for 12 sites

Table 5-2
Precipitation evaluation results for the 2019-2020 December-March season and for all seeded seasons

Target Group	Seeded Period	Ratio	Increase (inches)
E. Tooele Co.	36 Seeded Water Years	1.12	1.3
	2020 Water Year	0.98	-0.2
Primary Target	43 Seeded Water Years	1.12	1.3
	2020 Water Year	0.98	-0.2

The ratio shown in Table 5-2 is the ratio of average observed target area precipitation to average calculated target area precipitation, and the increase is the absolute increase in inches of water.

Table 5-3a
Eastern Tooele Co. (ETT) Target area
Summary of December - March precipitation evaluations

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1976	10.3	9.4	1.10	0.9
1977	6.6	6.9	0.96	-0.2
1978	20.7	16.3	1.27	4.4
1979	12.5	11.5	1.09	1.0
1980	19.6	15.8	1.24	3.8
1981	8.9	9.3	0.95	-0.5
1982	15.5	16.3	0.95	-0.8
1989	11.0	10.8	1.02	0.2
1990	9.8	7.7	1.27	2.1
1991	8.4	7.4	1.13	1.0
1992	7.4	7.4	1.01	0.1
1996	14.2	14.2	1.00	0.0
1997	15.0	12.9	1.16	2.1
1998	20.2	14.6	1.39	5.6
1999	9.3	8.8	1.05	0.5
2000	15.2	12.5	1.21	2.6
2001	9.4	8.3	1.12	1.0
2002	8.4	8.4	1.00	0.0
2003	8.7	7.6	1.14	1.1
2004	15.0	11.1	1.34	3.8
2005	15.4	13.4	1.15	2.0
2006	15.4	14.7	1.05	0.7
2007	9.9	8.3	1.19	1.6
2008	14.7	12.7	1.15	2.0
2009	13.6	13.2	1.03	0.4
2010	11.5	11.2	1.03	0.3
2011	16.6	14.9	1.11	1.6
2012	8.5	7.1	1.19	1.3
2013	9.5	8.3	1.15	1.2
2014	10.4	9.0	1.15	1.3
2015	6.2	6.0	1.03	0.2
2016	13.2	11.9	1.10	1.2
2017	18.8	16.8	1.12	2.0

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2018	8.6	7.8	1.10	0.8
2019	17.3	15.5	1.11	1.8
2020	8.4	8.6	0.98	-0.2
2021	9.4	9.0	1.04	0.4
Seeded Mean	**12.2**	**11.0**	**1.12**	**1.3**

Table 5-3b
Primary Target (PT) area
Summary of December - March precipitation evaluations

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1974	11.3	11.3	1.00	0.0
1975	12.8	12.1	1.06	0.7
1976	9.9	9.9	1.01	0.1
1977	6.4	4.6	1.40	1.8
1978	20.3	18.7	1.08	1.6
1979	16.3	14.5	1.12	1.8
1980	20.5	16.7	1.23	3.9
1981	9.3	8.0	1.16	1.3
1982	16.9	16.1	1.05	0.8
1983	17.5	15.0	1.17	2.5
1988	9.8	7.2	1.36	2.6
1989	10.2	10.3	0.99	-0.1
1990	9.1	7.8	1.17	1.3
1991	10.8	8.0	1.34	2.7
1992	10.2	7.6	1.34	2.6
1993	19.7	19.0	1.04	0.7
1994	8.7	6.5	1.35	2.3
1995	14.0	12.0	1.17	2.0
1996	12.9	12.2	1.05	0.7
1997	12.2	11.6	1.05	0.5
1998	14.4	12.6	1.14	1.8
1999	6.9	6.4	1.07	0.4
2000	12.4	10.8	1.15	1.7

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2001	9.5	6.8	1.39	2.7
2002	6.2	6.7	0.92	-0.6
2003	9.6	6.6	1.45	3.0
2004	11.0	9.2	1.20	1.8
2005	15.9	14.2	1.13	1.8
2006	13.7	13.1	1.04	0.5
2007	7.2	7.4	0.98	-0.2
2008	15.1	11.7	1.28	3.3
2009	13.1	11.6	1.13	1.5
2010	13.8	11.1	1.24	2.7
2011	16.6	14.3	1.16	2.3
2012	8.7	7.9	1.09	0.7
2013	9.2	8.9	1.04	0.4
2014	7.9	7.1	1.10	0.7
2015	8.4	7.7	1.09	0.7
2016	11.4	11.7	0.98	-0.3
2017	16.1	18.0	0.89	-2.0
2018	8.6	7.2	1.20	1.4
2019	15.7	15.3	1.03	0.4
2020	10.1	10.4	0.98	-0.2
2021	9.3	8.4	1.12	1.0
Seeded Mean	12.0	10.8	1.12	1.3

Eastern Tooele Target Precipitation Results

Seeding began in the ETT in 1976 and continued through the 1982 water year. Seeding resumed in 1989 and continued through 1992. After a break in seeding during water years 1993-95, seeding resumed in the 1996 water year and has been conducted each year through the present. Thus, there are 37 seeded seasons and 28 non-seeded seasons in the regression period. For the single season (2020-2021) evaluation, the regression equation resulted in an observed/predicted ratio of 1.04 as shown in these Table 5-3a. This is a 4% increase from that predicted by the control sites without seeding. It is important to remember that single-season evaluation results can vary significantly due to variability in precipitation patterns from one year to another, and, thus, a single-season result carries very little statistical significance. This variability primarily affects the results of the evaluation, not necessarily the actual effectiveness of the seeding. **During the 37 seeded seasons the observed precipitation within the target has averaged 12 percent greater than might have been expected from calculations based on the**

control precipitation averages. That increase is equal to an average additional 1.3 inches of water per seeded season. Note that the December-March evaluations do not estimate any possible additional effects of seeding which was conducted outside this four-month core evaluation period (e.g., November 15th-30th, April 1st-15th).

Figure 5.3 is a scatterplot showing a comparison between the seeded and non-seeded data sets in the eastern Tooele County precipitation linear regression. The linear regression equation (e.g. best linear fit to the historical non-seeded data, shown in black) is represented by the black diagonal line. Note that the vast majority of the seeded season data (red dots) lie above the regression line, indicative of greater target area precipitation in seeded seasons than that predicted from the regression equation based upon control area precipitation.

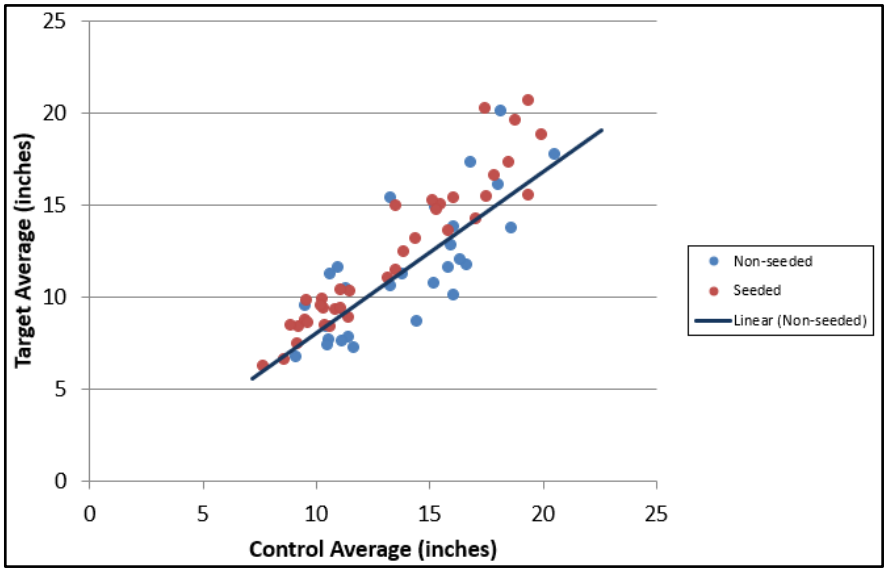


Figure 5.3 **Scatterplot of historical non-seeded (blue) vs seeded (red) data points for the eastern Tooele County precipitation evaluation. The diagonal line represents the linear regression equation for the non-seeded period.**

Primary Target Precipitation Results

Seeding was conducted in the target area beginning in the 1974 water year, continued until seeding was suspended in February 1983, and then discontinued entirely during water year 1984 because of excessively wet weather. However, seeding began again over portions of Washington County (mainly the Pine Valley Mountains) in 1985 and continued to spread northward in 1986 and 1987 into other parts of the target area. By 1988, seeding was again being conducted over essentially all of the previously seeded primary target area. The seeding program has continued to target most of the mountainous areas of central and southern Utah up through the current season. There have been 44 seeded seasons, excluding those when seeding was conducted over only a portion of the current target, and 18 seasons in the historical unseeded database. The 25 SNOTEL or cooperative observer sites located within the PT provide good coverage of the area targeted by cloud seeding. The high-density site coverage and distribution should ensure that the target area measurement sites are representative of the overall target area.

In the 2021 water year, the target/control precipitation evaluation results (from Table 5-2) yielded an observed/predicted ratio of 1.12, indicating that 12% more precipitation occurred in the target area than that predicted by control sites. As mentioned earlier, single-season results should be viewed with appropriate caution. **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 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 one-tail 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 results of this one regression evaluation being due to chance. The December-March evaluations do not estimate any possible effects of seeding which was conducted outside of this four-month core evaluation period (e.g., November 15th -30th or during April).

Figure 5.4 is a scatterplot similar to Figure 5.3. Again, note that almost all of the seeded seasons are above the regression line indicating increases in precipitation. Appendix C contains the historical and seeded regression equation information for both target areas.

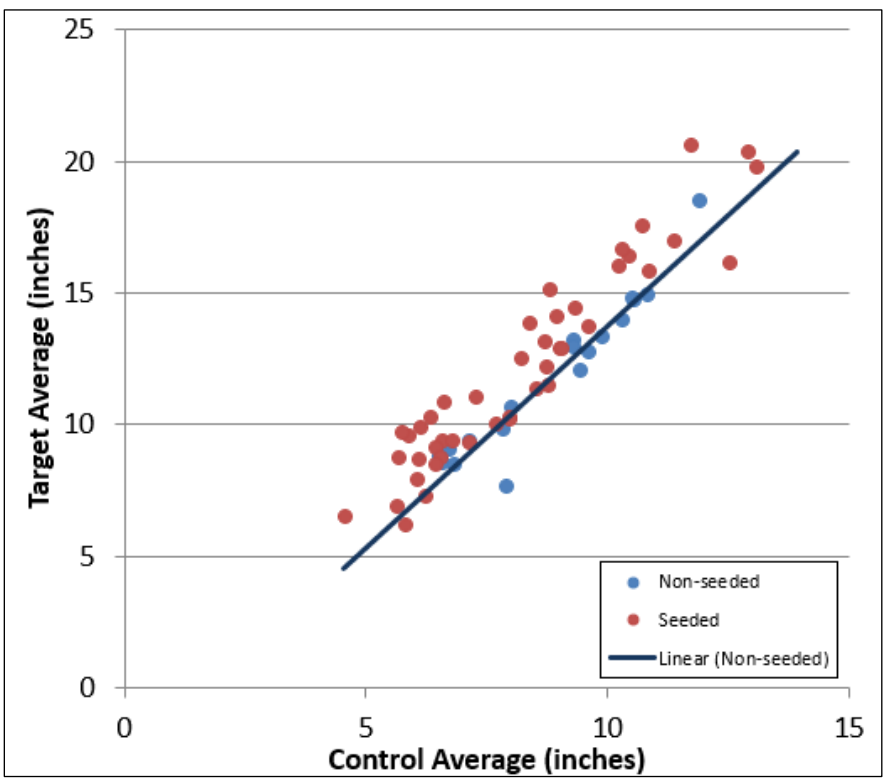


Figure 5.4 **Scatterplot of historical non-seeded (blue) vs seeded (red) data points for the primary target precipitation evaluation. The diagonal line represents the linear regression equation for the non-seeded period.**

5.4 Snow Water Equivalent (SWE) Evaluations

The procedure for evaluating the effect of cloud seeding on the snow water equivalent (SWE) as observed on April 1st was essentially the same as was done with the precipitation evaluations. In general,

the control area snow sites have been drawn from approximately the same areas as were used in the precipitation evaluation, but they are limited to the availability of higher elevation sites which have significant SWE accumulation.

Target Area SWE Sites

Many of the same target sites, either snow course or SNOTEL, that were used in the precipitation evaluation were also used in the SWE evaluation. The four target SWE site locations used for the ETT are shown in Figure 5.5 as X's. Two of these target sites are snow courses, while the other two are SNOTEL sites. The average elevation for the four target sites is 7,463 feet MSL.

A total of 30 target area SWE measuring sites were utilized in the Primary Target. Figure 5.6 shows target and control site locations. The average elevation for the target area sites is approximately 9,090 feet MSL. Actual site locations and elevations are listed in Appendix C for both target areas.

Control Area SWE Sites

The selection of sites in the control group was determined primarily by their degree of correlation with each target area. Thus, control area sites (for the ETT and the PT) were selected individually from a large number of potential sites available in surrounding regions and assessed regarding their effects on the control vs. target group correlations.

The control group used in the SWE evaluation for the Eastern Tooele County target area (ETT) consists of five snow measurement sites. These sites extend from southern Idaho (one site) through eastern Nevada (three sites) into the Wasatch Mountains of Utah (one site southeast of the target area). The correlation coefficient (r) of 0.79 indicates a moderately good correlation between control and target areas and is slightly lower than that for the shorter regression period (0.82). Detailed information on the five SNOTEL/snow course sites utilized in this control is given in Appendix C, and the sites are shown in Figure 5.5. The average elevation of the control group about 8,050 feet MSL. Some data estimation was necessary for one of the sites (Vernon Creek) for the period prior to 1967, as SNOTEL/snow course data were unavailable. The estimation was based on data at two other target sites closest to Vernon Creek (Rocky Basin Settlement and Bevan's Cabin).

The Primary Target control group consists of ten SNOTEL/snow course sites located from southern Idaho southward through eastern Nevada into north-central Arizona. This control group provided a good correlation ($r = 0.94$) with the Primary Target, with a variance (r^2) of 0.88, indicating that 88% of the variability in the historical data used to predict the expected snowpack was explained in the regression equation. The locations of the ten sites used as the control area are listed in the control section of Appendix C and are shown as yellow squares in Figure 5.6. The average elevation of this control group is 8,800 feet MSL.

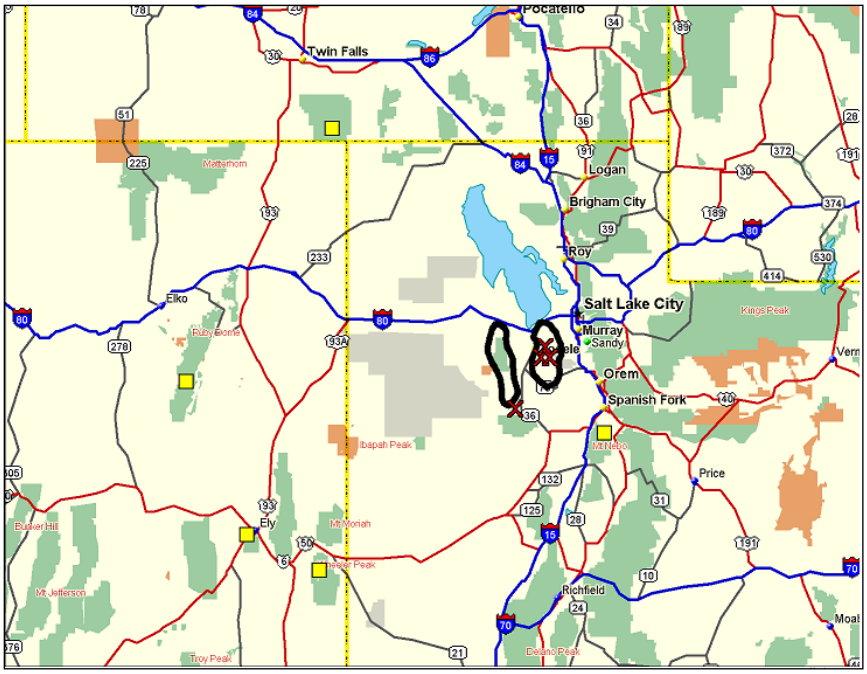


Figure 5.5 **SWE sites for Eastern Tooele target/control evaluation (squares are control sites, X's are target sites).**

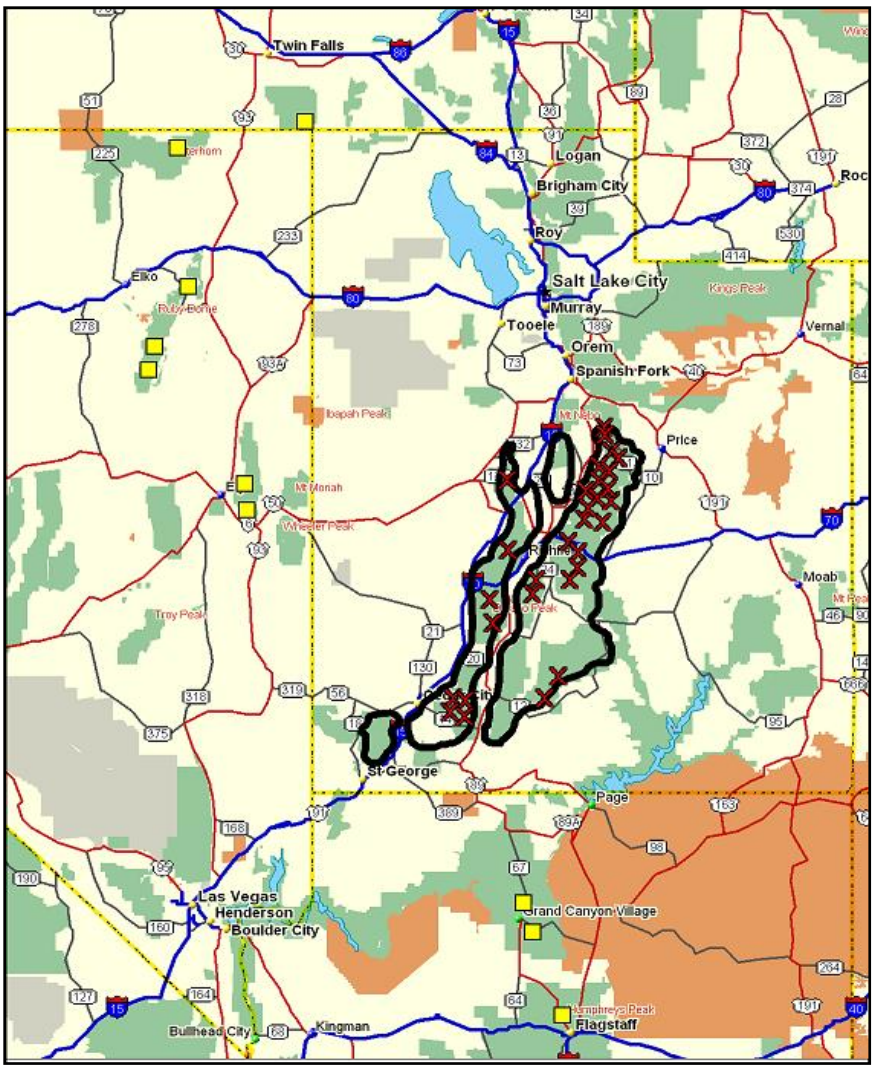


Figure 5.6 **SWE sites for Primary Target evaluation (squares are control sites, X's are target sites)**

SWE Regression Equation Development

The procedure was essentially the same as was done for the precipitation evaluation, i.e., control and target area stations were selected and average values for each were determined from the historical SWE data. The regression equation for the Tooele County SWE evaluation is based on a 29-year non-seeded period (1956-75, 1983-88, and 1993-95). The regression period for the primary target is shorter, consisting of 18 years (1957-73, and 1984). The SWE regression equations developed for the ETT and PT areas, using historical SNOTEL and estimated SNOTEL April 1st snow water content data, are provided in Table 5-4.

Table 5-4
Correlation coefficients, variances and regression equations for SWE evaluation

Target Group	Equation	Corr Coeff (r)	Variance (r^2)
Eastern Tooele (ETT)	YC = 1.069(X5) – 0.81	0.77	0.59
Primary Target (PT)	YC = 1.04(X10) - 0.38	0.94	0.88

Where:

Y_C = Average calculated SWE for target (April 1st)

X_5 = Average three state (ID/NV/UT) control area SWE (April 1st) for 5 sites

X_{10} = Average three state (AZ/ID/NV) control area SWE (April 1st) for 10 sites

Results of Snow Water Content Analyses

The results of the snow water evaluations for current water year and the average for all seeded seasons for the ETT and PT are presented in Table 5-5. In some seasons, a large number of SNOTEL sites have experienced large decreases from peak SWE (10-50+%) prior to April 1st. For this reason, April 1st SWE evaluation results for water years 2007, 2012, 2015 and 2017 were excluded due to excessive pre-April 1st snow melt. Tables 5-6 and 5-7 list the results for each seeded season for the ETT and PT, respectively. Appendix D contains the historical and seeded year regression equation and evaluation result information for both target areas.

Table 5-5
Snow water content evaluation results for the 2020-2021 season, and for all seeded seasons

Target Group	Seeded Period	Ratio Y_o/Y_c	Increase Y_o-Y_c
Eastern Tooele (ETT)	33 water years*	1.10	1.3
	2021 water year	0.95	-0.5
Primary Target (PT)	40 water years*	1.04	0.6
	2021 water year	1.00	0.1

* 2007, 2012, 2015 and 2017 results not included in long-term mean due to excessive pre-April 1st snow melt

The ratios shown in Table 5-5 are ratios of average observed target area SWE to average calculated target area SWE. The increase is the average difference (in inches) between observed and calculated water content in snowpack at target gauges on April 1st.

Eastern Tooele Results

Table 5-5 shows the Eastern Tooele target group snow water evaluation results for the current water year and for all seeded seasons. As in the SWE evaluation for the Primary Target area, the 2007, 2012, 2015 and 2017 (April 1) Tooele County SWE evaluation results are excluded from the long-term mean due to excessive pre-April 1st snowmelt. Table 5-6 shows individual year results for the ETT SWE

evaluation. The long-term result of this evaluation, a ratio of 1.10 equivalent to a 10% increase, is also close to the 1.12 ratio for the ETT precipitation evaluation (see Table 5-2 for comparison). The difference in observed versus calculated snow water (in inches of water) showed an average of about 1.3 inches more water observed than calculated per year for both (snow and precipitation) analyses in the Tooele County portion of the program. Results for the current season are also shown (a ratio of 1.08 which suggests an 8% increase), although it should again be emphasized that single-season results carry very little statistical significance.

Table 5-6
Eastern Tooele Co. (ETT) Target area, April 1st snow water content evaluation

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1976	15.6	16.0	0.98	-0.4
1977	9.3	5.8	1.59	3.5
1978	21.1	17.8	1.18	3.3
1979	18.0	19.4	0.93	-1.4
1980	24.4	19.5	1.25	4.8
1981	12.5	9.2	1.36	3.3
1982	19.6	22.1	0.89	-2.5
1989	9.9	14.1	0.70	-4.2
1990	12.4	10.7	1.16	1.7
1991	10.5	10.1	1.05	0.5
1992	10.3	8.5	1.21	1.8
1996	12.8	14.7	0.87	-1.9
1997	17.9	15.0	1.19	2.9
1998	23.4	15.0	1.56	8.4
1999	8.8	10.0	0.88	-1.2
2000	15.9	11.2	1.42	4.7
2001	11.4	8.5	1.35	3.0
2002	11.0	11.2	0.98	-0.2
2003	9.6	8.3	1.16	1.3
2004	15.0	10.1	1.49	4.9
2005	20.2	18.5	1.09	1.7
2006	16.3	17.0	0.96	-0.6
2007*	7.2	6.4	1.11	0.7
2008	17.5	14.4	1.21	3.1
2009	13.9	12.6	1.10	1.2
2010	13.0	12.2	1.06	0.8
2011	21.9	16.3	1.34	5.5
2012*	7.2	7.9	0.91	-0.7
2013	10.0	7.7	1.30	2.3

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2014	8.3	9.9	0.83	-1.7
2015*	1.5	3.6	0.43	-2.0
2016	12.0	13.8	0.87	-1.8
2017*	13.8	13.0	1.06	0.8
2018	5.3	8.1	0.66	-2.8
2019	21.4	20.0	1.07	1.4
2020	11.5	10.7	1.08	0.8
2021	10.8	11.3	0.95	-0.5
Seeded Mean	14.3	13.0	1.10	1.3

* Results excluded from long-term average due to excessive early-season snowmelt

Primary Target Results

Table 5-7 shows the individual and combined season results of the April 1st SWE evaluation for the Primary Target areas. As discussed in the previous section, the 2007, 2012, 2015 and 2017 April 1st SWE evaluation results are excluded from the long-term mean due to excessive early season snowmelt in those seasons. The data for the combined seeded seasons included in the evaluation indicates a ratio of observed to calculated snow water of 1.04. This ratio (1.04) is much less than the ratio of 1.12 for the precipitation evaluation for this primary target group, and the resulting statistical significance (one-tail P value of 0.29) is less as well. Indications of excess snow water content provided by the SWE evaluation are also less than in the precipitation results, with an average of 0.6 inches per year in the snow water analysis and 1.3 inches per year indicated by the precipitation evaluation. These differences are discussed in section 5.7.

Table 5-7
Primary Target (PT) area
April 1st snow water content evaluation

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1974	15.6	14.0	1.11	1.6
1975	17.3	18.3	0.95	-1.0
1976	12.9	12.8	1.01	0.2
1977	8.2	8.0	1.02	0.2
1978	21.8	18.9	1.15	2.9
1979	21.4	18.2	1.17	3.2
1980	23.6	19.6	1.20	4.0
1981	10.2	9.6	1.06	0.6

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1982	20.5	20.7	0.99	-0.2
1983	26.0	23.6	1.10	2.4
1988	13.1	10.5	1.25	2.7
1989	11.3	14.6	0.77	-3.4
1990	10.5	9.1	1.16	1.4
1991	12.8	12.3	1.04	0.5
1992	12.1	11.7	1.04	0.4
1993	21.3	20.4	1.04	0.9
1994	10.8	9.3	1.17	1.6
1995	16.6	18.0	0.92	-1.4
1996	14.6	13.8	1.06	0.8
1997	15.1	15.7	0.96	-0.6
1998	16.7	17.4	0.96	-0.7
1999	8.1	10.3	0.79	-2.2
2000	13.7	12.9	1.06	0.8
2001	11.3	10.8	1.04	0.5
2002	9.6	10.4	0.92	-0.8
2003	12.1	9.5	1.28	2.6
2004	10.2	9.2	1.11	1.0
2005	20.1	21.1	0.95	-1.0
2006	17.4	16.9	1.03	0.5
2007*	6.8	7.8	0.87	-1.0
2008	16.1	15.2	1.06	0.8
2009	12.7	13.0	0.98	-0.2
2010	15.1	14.8	1.02	0.3
2011	20.1	16.2	1.24	3.9
2012*	7.9	7.1	1.11	0.8
2013	9.3	8.8	1.06	0.5
2014	9.9	9.4	1.05	0.5
2015*	6.1	4.7	1.28	1.3
2016	12.8	14.4	0.89	-1.5
2017*	13.9	16.6	0.84	-2.7
2018	7.9	8.1	0.97	-0.2

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2019	19.5	18.9	1.03	0.6
2020	14.0	11.6	1.21	2.4
2021	11.0	10.9	1.00	0.1
Seeded Mean	14.6	14.0	1.04	0.6

* Results not included in long-term average due to excessive early-season snowmelt

5.5 Multiple Linear Regression Analyses

A variation of the linear regression technique is a multiple linear regression. In the linear regression averages of the control site data and target site data are used in development of the equation. In a multiple linear regression typically an average of all the target site data is correlated with each individual control site resulting in an equation with a number of terms depending upon the number of control sites. Past work with multiple linear regression evaluations highlighted some potential problems with this type of evaluation under certain circumstances. For example, a multiple linear regression equation containing independent control variables (such as single control sites) that are too similar to each other may yield an unrealistic regression equation. Such an equation typically produces highly variable results (that is, very high and/or very low individual season observed/predicted ratios) when applied to seeded season data.

One way to reduce or eliminate problems with the multiple regression analysis is to group control sites into two or more sets, with each set containing an average of a grouping of control sites. Ideally, control sites with similar characteristics (such as those at a higher latitude in comparison to much of the target area, and those at a lower latitude) can be grouped for this purpose, allowing the multiple linear regression equation to distinguish between the two groups in a meaningful way. Testing the standard deviation of the resulting individual seeded year ratios provides a useful comparison between a linear and corresponding multiple linear regression technique. Although a multiple linear regression equation containing the same control sites will typically have a better correlation (higher r-value) than the linear, ideally the resulting individual year observed/predicted ratios should have less variability (lower standard deviation) as well. This indicates that the multiple linear regression equation is helping to reduce some of the natural variability or “noise” inherent in the target /control relationship.

Most of the multiple linear regression equations developed for the southern/central Utah seeding program produced much more variable individual seeded season results than did the linear regression equations, and so the results from most of these have not been considered reliable for evaluation of this program. However, for the primary target area, it was found that a multiple linear SWE regression equation containing two control sets (one an average of the five northern-most control sites, and the other an average of the five southern-most sites) reduced the variability in the seeded season results slightly. For the combination of all seeded seasons, this multiple linear SWE regression produced an observed/predicted ratio of 1.03 (similar to the 1.04 long-term result for the linear regression equation).

5.6 Double Mass Plots

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. Figures 5.7 and 5.8 provide plots of the data used by NAWC in target area evaluations of December – March precipitation, for the Primary Target and Eastern Tooele County Target areas. Target and control area-average seasonal values for both the historical (not-seeded) and the seeded periods are plotted on the figures. The December – March precipitation data are used in these plots since these data best represent the seeded season. The plotted values are cumulative; each new season is added to the sum of all of the previous seasons. In each figure, a line has been drawn through the points during the not-seeded base period. The plots show stable linear relationships prior to the beginning of cloud seeding. For comparison with the seeded period, the line describing the not-seeded period is extended at a constant slope through the seeded period. The Eastern Tooele County plot (Fig. 5.8) is more complex since there were two non-seeded intervals (from 1983-88 and 1993-95) even after the beginning of initial seeding operations in 1976. However, the line in this plot is drawn to fit the pre-seeding historical period of 1957-1975.

Figures 5.7 and 5.8 show a distinct 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 at approximately the same time as the start of the cloud seeding programs in the mid to late 1970s. Beginning at/near this time the plots in each case show generally greater precipitation in the target area compared to the control area. 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.

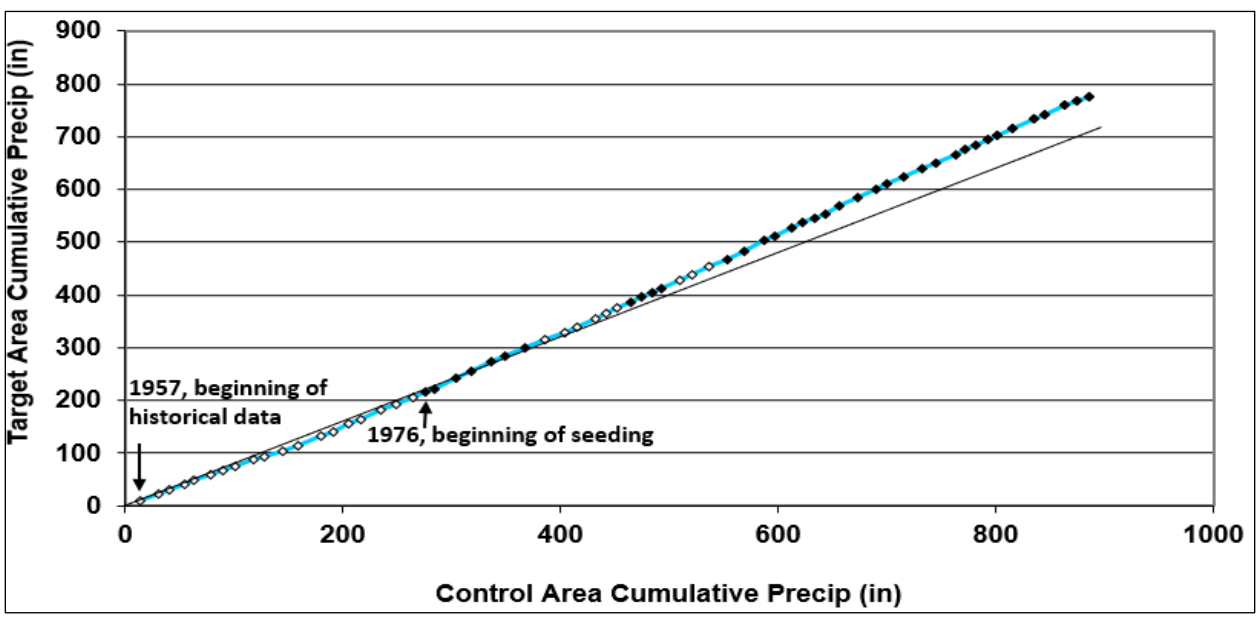


Figure 5.7 **Double-Mass plot for Primary Target; all seasons shown after 1974 in this plot were seeded, and all the seasons plotted previous to this were not seeded.**

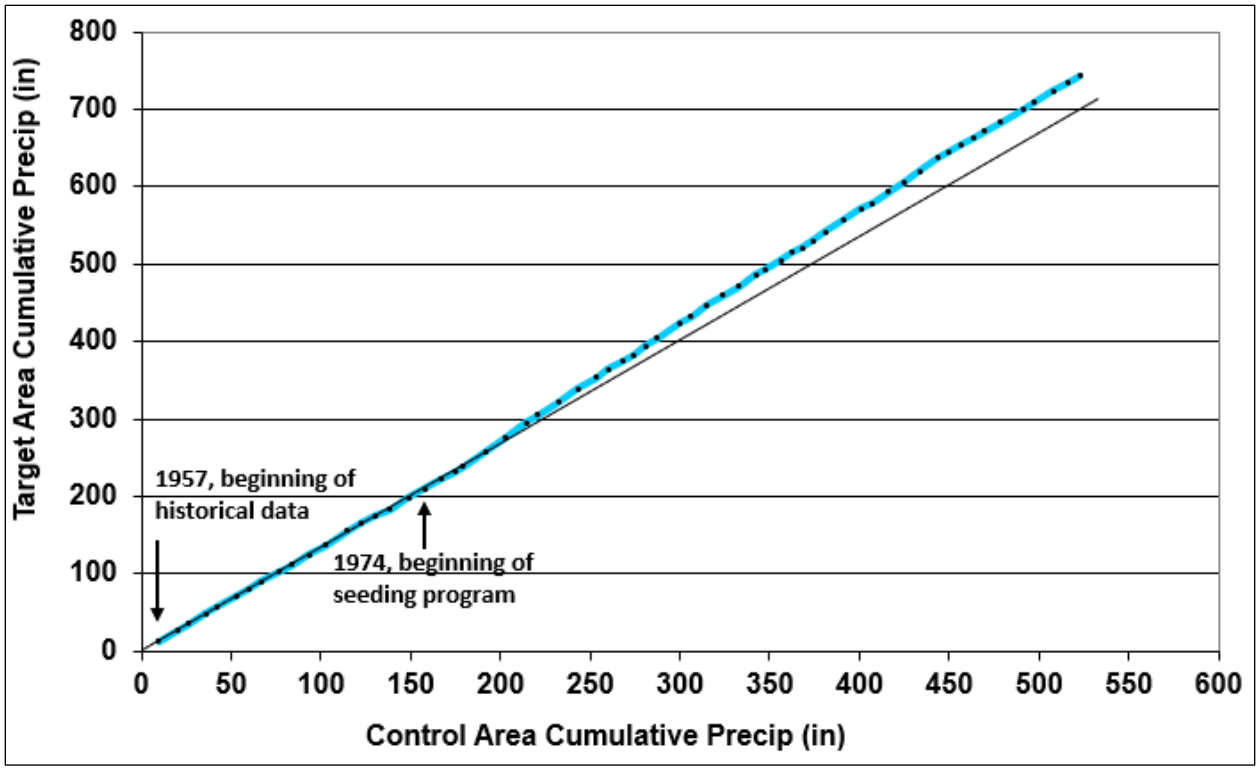


Figure 5.8 **Double-Mass plot for Eastern Tooele County Target; smaller data points denote non-seeded seasons, and larger, darker points are the seeded seasons**

5.7 Summary of Evaluation Results

Table 5-8 summarizes the results of the seeding evaluations, both for the ETT and PT target areas, for precipitation and SWE. Combined results of all seeded season evaluations suggest an approximate 10-12% increase in precipitation/snow water for the ETT, with a range of 3-12% increases indicated for the PT in the various linear and multiple linear regression evaluations.

Table 5-8
Summary of ratios from precipitation and SWE evaluations

	2021 Water Year	Long-term Average
ETT Precipitation Linear	1.04	1.12
ETT SWE Linear	0.95	1.10
PT Precipitation Linear	1.12	1.12
PT SWE Linear	1.00	1.04

The reader will note the significant differences in long-term average results between the precipitation and SWE analyses, which have persisted even though the target and control groups have had minor adjustments over time (usually due to loss of site data availability), resulting in various combination of sites having been examined in regression equations. One factor involved in this difference is that SWE accumulation usually begins before the seeded portion of the season, and therefore the seeding effects on snow water content are diluted by the early season non-seeded period. The seeding program in some years has ended by mid-March, making this a potential factor in the spring as well. Also,

it was determined that the change in SWE measurement methods (the advent of SNOTEL) which occurred in about 1980, and the ensuing data adjustments applied by NRCS, may result in an underestimate of seeding effects in the SWE evaluation for the Primary Target, as was discussed in further detail in some past reports. Based on these considerations, it is concluded that (at least for the Primary Target area) the estimates of cloud seeding effectiveness based on December through March precipitation may be more reliable than those based upon April 1st snow water content.

As a side note, the December-March precipitation evaluations do not estimate any possible effects of seeding which was conducted outside of this four-month core evaluation period (e.g., November 15-30 or during April). NAWC performed an analysis of the potential increases in streamflow from these extension periods (Griffith et al., 2010) 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.

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APPENDIX A - SUSPENSION CRITERIA

Certain situations require temporary or longer-term suspension of cloud seeding activities, with reference to well-considered criteria for consideration of possible suspensions, to minimize either an actual or apparent contribution of seeding to a potentially hazardous situation. The ability to forecast (anticipate) and judiciously avoid hazardous conditions is very important in limiting any potential liability associated with weather modification and to maintain a positive public image.

There are three primary hazardous situations around which suspension criteria have been developed. These include:

1. Excess snowpack accumulation
2. Rain-induced winter flooding
3. Severe weather

1. Excess Snowpack Accumulation

Snowpack begins to accumulate in the mountainous areas of Utah in November and continues through April. The heaviest average accumulations normally occur from January through March. Excessive snowpack water content becomes a potential hazard during the resultant snowmelt. The Natural Resources Conservation Service (NRCS) maintains a network of high elevation snowpack measurement sites in the State of Utah, known as the SNOTEL network. SNOTEL automated observations are now readily available, updated as often as hourly. The following set of criteria, based upon observations from these SNOTEL site observations, has been developed as a guide for potential suspension of operations.

Snowpack-related suspension considerations will be assessed on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne River, Price-San Rafael, Dirty Devil, Southeastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. The Weber-Ogden and Provo River – Utah Lake – Jordan River criteria apply to suspension considerations for the Western Uintas project. Since SNOTEL observations are available on a daily basis, suspensions (and cancellation of suspensions) can be made on a daily basis using linear interpolation of the first of month criteria. For the Southern and Central Utah Program, there are 10 listed SNOTEL sites with date-specific snow water equivalent criteria on which suspension decisions can be based.

Streamflow forecasts, reservoir storage levels, soil moisture content and amounts of precipitation in prior seasons are other factors which need to be considered when the potential for suspending seeding operations due to excess snowpack water content exists.

2. Rain-induced Winter Floods

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

3. Severe Weather

During periods of hazardous weather associated with both winter orographic and convective precipitation systems it is sometimes necessary or advisable for the National Weather Service (NWS) to issue special weather bulletins advising the public of the weather phenomena and the attendant hazards. Each phenomenon is described in terms of criteria used by the NWS in issuing special weather bulletins. Those that may be relevant in the conduct of winter cloud seeding programs include the following:

- Winter Storm Warning - This is issued by the NWS when it expects heavy snow warning criteria to be met, along with strong winds/wind chill or freezing precipitation.
- Flash Flood Warnings - This is issued by the NWS when flash flooding is imminent or in progress. In the Intermountain West, these warnings are generally issued relative to, but are not limited to, fall or spring convective systems.

Seeding operations may be suspended whenever the NWS issues a weather warning for or adjacent to any target area. Since the objective of the cloud seeding program is to increase winter snowfall in the mountainous areas of the state, operations will typically not be suspended when Winter Storm Warnings are issued, unless there are special considerations (e.g., a heavy storm that impacts Christmas Eve travel).

Flash Flood Warnings are usually issued when intense convective activity causing heavy rainfall is expected or is occurring. Although the probability of this situation occurring during our core operational seeding periods is low, the potential does exist, especially over southern sections of the state during late March and early April, which can include the project spring extension period. The type of storm that may cause problems is one that has the potential of producing 1-2 inches or greater of rainfall in approximately a 24-hour period, combined with high freezing levels (e.g., > 8,000 feet MSL). Seeding operations will be suspended for the duration of the warning period in the affected areas.

NAWC's project meteorologists have the authority to temporarily suspend localized seeding operations due to development of hazardous severe weather conditions even if the NWS has not issued a warning. This would be a rare event, but it is important for the operator to have this latitude.

APPENDIX B - SEEDING OPERATIONS TABLES

Table B-1
Generator Hours – Central and Southern Utah, 2020-2021
Storms 1-9

Storm	1*	2*	3	4	5	6	7	8	9
Dates	Nov 7-9	Nov 13-14	Nov 25-26	Dec 12	Dec 14-15	Dec 17-18	Dec 28-29	Jan 4-5	Jan 8-9
SITES									
10-1			12			13.75		9	
10-2									
10-3						7		9	
10-4								9	
10-6						4.5			
10-7								10.5	
10-8						5.5		9	
10-9			12.25			12		8	
10-10						4.25			
10-11								10.5	
10-12								9	
11-1		14.5				11		10	
11-2									
11-3				6.75		10.75		7.5	
11-4				6.75				9	11
11-5		9				11		9	
13-1						10			12.5
13-3	10.5	16		7	15.25	10.5		9	
13-4		14.5							11.5
13-5	11.25	14.5	10						
13-6	10	14				17.25		9	10.5
13-7		14.75		7.5		11.25		8.5	
13-8	8.5	14.5		7				10	11.75
13-9				7	5	17.25		10	
13-10	13	8		7.25	15.5			9	

Storm	1*	2*	3	4	5	6	7	8	9
Dates	Nov 7-9	Nov 13-14	Nov 25-26	Dec 12	Dec 14-15	Dec 17-18	Dec 28-29	Jan 4-5	Jan 8-9
SITES									
13-11		13.5		7		11		9	11.75
13-12	11.25	14.5	10						11
14-1						11.25		8	12
14-2						11.25		8	12
14-3								8	
14-4				7.25					11.5
14-5			10	8	5.5	13		8	6
14-6			10	7	5	13.25		8	12
14-7				7.75		13.25		8	
17-1		11				13			
17-2		11		11		17.75			
17-3	16.25					17.75		10	
17-4		11				17.75		9	
17-5	16.25	11		6.5	6.25	7		10	
17-6					6.5	10			
17-7	42.75			8.5	4	10.25	14.75		
17-8	42.25								
17-9	43	3.25		8	5	10			
17-10	43			11	4.5	10			
18-1				7	5.75	17.5			
18-2	5	15.75		7.25		17.25		8	11.5
21-1				7.75		11.75	15		
21-2	15.75						4		
21-5	6								
21-8						13	11		
21-9						13	13.25		
21-10						11.5			
21-11	15.5			8.5		12.5	14.75		
21-12	15.75								
21-13	24								
21-14	5.25					8	16.75		

Storm	1*	2*	3	4	5	6	7	8	9
Dates	Nov 7-9	Nov 13-14	Nov 25-26	Dec 12	Dec 14-15	Dec 17-18	Dec 28-29	Jan 4-5	Jan 8-9
SITES									
21-17				8.75		10.5			
22-1	23.75						5.5		
22-2	23.75						6.5		
22-3	43.25					11.5			
22-4							6.5		
22-5	24			7.5	10				
22-7	18.25			8.5		13			
22-8	29.75			8		14	18.25		
22-9				10	10	13	18.25		
22-10	15.75								
22-11	5.5			7.75			17		
22-15	23.75								
22-16	21.5						5.5		
Storm Total	**584.5**	**210.75**	**64.25**	**212.75**	**98.25**	**499**	**167**	**259**	**145**

* Seeding funded through Lower Basin Extension

Table B-2
Generator Hours – Central and Southern Utah, 2020-2021
Storms 10-18

Storm	10	11	12	13	14	15	16	17	18
Dates	Jan 22-24	Jan 25-26	Jan 29-30	Feb 3-4	Feb 5-6	Feb 12	Feb 13-14	Feb 15-17	Feb 20
SITES									
10-1			10	7	3.75		14	20.5	
10-2	21		7	4				12	
10-3			12.5					38.5	
10-4			4						
10-6	6		11	6			15	27.5	
10-7	6		10.25	9				3	
10-8			5						
10-9	20.75		12						
10-10			13	7.5			14.75	30	
10-11	6		10.25	9				18.5	
10-12							15	35.5	
11-1			10	18	5.75		17	29.25	
11-2				16			12.25		
11-3			10.25	20.5			16.5	39	
11-4			10	10			15	42.5	
11-5			10.25	10	6.5				
13-1			10.5	12			15	20	
13-3			9	22	6.5		16.5	38	2.25
13-4			10.5	12	5.75		15.5		4.5
13-5				12	5		17	38	
13-6	13.5		11.75				15.5		
13-7	13.25		12.25				16.5	39.25	4.25
13-8			14.25	11.25	6.25		16.5	41.5	5
13-9	13.5		15	18			16.5		
13-10			14.75	11.5			11.5		
13-11	13.25		12	11	5		16.5		2.75
13-12			14.25	11			15.5	41	
14-1			10.5	3			16.75		

Storm	10	11	12	13	14	15	16	17	18
Dates	Jan 22-24	Jan 25-26	Jan 29-30	Feb 3-4	Feb 5-6	Feb 12	Feb 13-14	Feb 15-17	Feb 20
SITES									
14-2			11	7.5			16.25		
14-3								24	
14-4			11.5				15.25		
14-5			11	9			17.25	33	
14-6			11	17.5			16.5	25	
14-7			12.75	17.5			10		
17-1	18			6.25			20.5		
17-2	18		18.5	6.25			17.25		
17-3	13			7			17.5		
17-4	12.5		12.25				17.5		
17-5	11			7.5					
17-6	13		16	5.5			16		
17-7	17.5	11	10				16		4.25
17-8	16.5		6						
17-9	18.5	11	16.5				17.25		4.25
17-10	14		18.25	4.75			16.75		4
18-1	13.75			7.5			18		
18-2	13.25		15	22	6		16.5		
21-1	15.5		12.75				18		4
21-2	12	13	12				5.25		
21-5	11		7						
21-8							8.25		
21-9			13				18		
21-10			12.25				19.25		4.5
21-11	11.5	13	6				19.75		
21-12	13.25		6						
21-13	18.75								
21-14	13.75						19.5		4.5
21-17	18.25		12.75				17.25		4
22-1	18.75	21	9						
22-2	18	22	11.25				5.75		

Storm	10	11	12	13	14	15	16	17	18
Dates	Jan 22-24	Jan 25-26	Jan 29-30	Feb 3-4	Feb 5-6	Feb 12	Feb 13-14	Feb 15-17	Feb 20
SITES									
22-3			8.75						
22-4	18	17	8.75				20.5		4.25
22-5							0		
22-7	18	11	2				19.75		
22-8	19.5	16	20.5			4	11		3
22-9	17		11.5			3.5			
22-10	13.25		5.5						
22-11	16		11				12.25		
22-15	18	22.75	6.75						
22-16	15	22.5	7.75						
Storm Total	**577.75**	**180.25**	**624.5**	**359**	**50.5**	**7.5**	**751.75**	**596**	**55.5**

Table B-3
Generator Hours – Central and Southern Utah, 2020-2021
Storms 19-27

Storm	19	20	21	22	23	24*	25*	26*	27*
Dates	Feb 24	Feb 27	Mar 3-4	Mar 10-11	Mar 12-13	Mar 15-16	Mar 20-21	Mar 21	Mar 23
SITES									
10-1									
10-2									
10-3				3					
10-4				4.25					
10-6									
10-7									
10-8									
10-9		6.25							
10-10									
10-11									
10-12									
11-1							15		
11-2									
11-3		6							
11-4		5.75							
11-5		5.75					13.75	4.25	
13-1		5.75							
13-3							15.75	4.75	
13-4							15.75	4.5	
13-5							15.75		
13-6							13.5		
13-7							15.5		
13-8							16.75		
13-9							12.75		
13-10							15.75		
13-11							15		
13-12							15.5	4.75	
14-1		6							

Storm	19	20	21	22	23	24*	25*	26*	27*
Dates	Feb 24	Feb 27	Mar 3-4	Mar 10-11	Mar 12-13	Mar 15-16	Mar 20-21	Mar 21	Mar 23
SITES									
14-2		5.75							
14-3		5.5							
14-4									
14-5		5.75							
14-6		5.75							
14-7		6							
17-1			15.5				14.5		
17-2			12.75				15.5		
17-3			15				15.5		
17-4	4.25						14.5		
17-5	4		15				14.5		
17-6	3.5		13	12			9.75		
17-7			15.75	23.25	9	5.5			6.25
17-8			13.5	20.75	5	10			6.25
17-9			15.5	23.5		6	13.5		
17-10			13.5	23			13.75		
18-1	4						15.5		
18-2							15.5	4.5	
21-1					4		4.5		
21-2					7				
21-5			12	24.25					
21-8									
21-9									
21-10		5.75					4		
21-11					10.5				
21-12									
21-13			12.5	14.75					
21-14					8.75		4.25		
21-17					9.75		4.75		
22-1			11	23.5					
22-2				27	7	17.25			

Storm	19	20	21	22	23	24*	25*	26*	27*
Dates	Feb 24	Feb 27	Mar 3-4	Mar 10-11	Mar 12-13	Mar 15-16	Mar 20-21	Mar 21	Mar 23
SITES									
22-3				23	10.25				
22-4			12.25	23	6.75	5.75			
22-5			13.25	23.25	10	5.75			
22-7			16	24	6.75		15		
22-8				26	2.5	22			
22-9				25.25	9.5				
22-10									
22-11					21.25				
22-15			11.75	25.25	6.5	12			
22-16			10	26.5	8	15			
Storm Total	15.75	70	228.25	395.5	142.5	99.25	355.75	22.75	12.5

* Seeding funded through lower basin extension

Table B-4
Generator Hours – Central and Southern Utah, 2020-2021
Storms 28-33

Storm	28**	29*	30**	31#	32#	33#	Site Totals
Dates	Mar 26	Apr 14	Apr 15	Apr 16	Apr 26	Apr 27	
SITES							
10-1							90
10-2							44
10-3							70
10-4							17.25
10-6							70
10-7							38.75
10-8							19.5
10-9							71.25
10-10							69.5
10-11							54.25
10-12							59.5
11-1	8.25				8	9	155.75
11-2							28.25
11-3	6.5		6.25		8		138
11-4	5		6		8.5		129.5
11-5	8		7.25				94.75
13-1	6.75				7.75		100.25
13-3	8.5	7	6.75	9.25	8.5		223
13-4	6			8.5	8		117
13-5	8.5		7	8.75		9.75	157.5
13-6			7.25				122.25
13-7	6.25				8.75		158
13-8	12.25	8.25	7.25				191
13-9			7.25				122.25
13-10	7	6.75		8.75	7.75		136.5
13-11	8.75	6.5	7		8.75	9	167.75
13-12	8.25	6.75	7	8.75	8		187.5

Storm	28**	29*	30**	31#	32#	33#	Site Totals
Dates	Mar 26	Apr 14	Apr 15	Apr 16	Apr 26	Apr 27	
SITES							
14-1							67.5
14-2							71.75
14-3							37.5
14-4							45.5
14-5							126.5
14-6							131
14-7							75.25
17-1			7.75				106.5
17-2			6.25				134.25
17-3			8.5				120.5
17-4			8.75				107.5
17-5			6.5				115.5
17-6			8.25				113.5
17-7			7.75				206.5
17-8							120.25
17-9	5		8				208.25
17-10			5.25				181.75
18-1			7.25				96.25
18-2	6.5	7	6.75		9	9.5	196.25
21-1							93.25
21-2							69
21-5							60.25
21-8							32.25
21-9							57.25
21-10							57.25
21-11							112
21-12							35
21-13							70
21-14							80.75
21-17							86
22-1	3.75						116.25

Storm	28**	29*	30**	31#	32#	33#	Site Totals
Dates	Mar 26	Apr 14	Apr 15	Apr 16	Apr 26	Apr 27	
SITES							
22-2	5.5						144
22-3							96.75
22-4							122.75
22-5	5.25						99
22-7			6				158.25
22-8	5.5		7				207
22-9	5.5		7.5				131
22-10							34.5
22-11	5.5						96.25
22-15							126.75
22-16							131.75
Storm Total	142.5	42.25	170.5	49	91	37.25	

* Seeding funded through Lower Basin extension

** Includes seeding for Lower Basin and 3-county extension

Seeding for 3-county extension only; April 16 event includes 5 hours from another program site

APPENDIX C - EVALUATION TARGET AND CONTROL SITES

PRIMARY TARGET - PRECIPITATION

Site	Lat(N)	Long(W)	Elev (Ft)
Control Sites			
Bear Creek Tel, Nv	41°50'	115°27'	8040
Berry Creek Tel, Nv	39°21'	114°39'	9100
Caliente, NV	37°37'	114°31'	4440
Ely, NV	39°17'	114°51'	6250
Flagstaff Airport, AZ	35°08'	111°40'	7000
Jacks Peak Tel, NV	41°32'	116°01'	8420
McGill, Nv	39°24'	114°46'	6340
Pole Creek RS, Tel Nv	41°52'	115°15'	8330
Seligman, Az	35°19'	112°53'	5250
Seventy-Six Ck Tel Nv	41°42'	115°28'	7100
Ward Mountain, Tel #2 Nv	39°08'	114°49'	9200
Wupatki NM, Az	35°31'	111°22'	4908
Target Sites			
Alton	37°26'	112°29'	7040
Beaver Dams	39°08'	111°33'	8000
Big Flat	38°18'	112°21'	10290
Black Fl. UM Ck.	38°41'	111°36'	9400
Box Creek	38°30'	112°02'	9300
Buck Flat	39°08'	111°27'	9800
Castle Valley	37°40'	112°44'	9580
Dills Camp	39°02'	111°28'	9200
Farnsworth Lake	38°46'	111°40'	9600
Gooseberry R.S.	38°48'	111°41'	7920
Hatch	37°39'	112°26'	6910
Kimberly Mine	38°29'	112°23'	9300
Kolob	37°32'	113°03'	9250
Little Grassy Ck.	37°29'	113°51'	6100
Long Flat	37°30'	113°25'	8000
Mammoth-Cottonwood	39°41'	111°19'	8800
Merchant Valley	38°18'	112°26'	8750
Midway Valley	37°34'	112°50'	9800
Pickle Keg Spring	39°02'	111°35'	9600
Pine Creek	38°53'	112°15'	8800

PRIMARY TARGET - PRECIPITATION (continued)

Site	Lat(N)	Long(W)	Elev (Ft)
Target Sites			
Red Pine Ridge	39°27'	111°16'	9200
Scofield-Skyland Mine	39°41'	111°12'	8710
Seeley Ck. R.S.	39°19'	111°26'	10000
Webster Flat	37°35'	112°54'	9200
Widtsoe-Esc. # 3	37°50'	111°53'	9500

EASTERN TOOELE TARGET - PRECIPITATION

Control Sites			
Berry Creek, NV	39°21'	114°39'	9100
Diamond Peak, NV	39°34'	115°51'	8040
Farmington Cyn Upr, UT	40°58'	111°48'	8000
Lamoille #3, NV	40°38'	115°24'	7700
Payson R.S., UT	39°56'	111°38'	8050
Ward Mtn #2, NV	39°08'	114°49'	9200
Target Sites			
Rocky Basin Setlmnt, UT	40°26'	112°13'	8900
Tooele, UT	40°32'	112°18'	5072
Vernon Creek, UT	39°56'	112°25'	7500

PRIMARY TARGET - SNOW COURSE AND SNOW PILLOW

Site	Lat(N)	Long(W)	Elev (Ft)
Control Sites			
Bright Angel Sc, Az	36°13'	112°04'	8400
Grand Canyon Sc, Az	35°58'	111°58'	7500
Snowbowl #2 Sc, Az	35°19'	111°42'	11,200
Bostetter RS Pil, Id	42°10'	114°11'	7500
Berry Creek, Pil, Nv	39°21'	114°39'	9100
Dorsey Basin Pil, Nv	40°53'	115°12'	8100
Site	**Lat(N)**	**Long(W)**	**Elev (Ft)**
Green Mountain Pil, Nv	40°23'	115°32'	8000
Corral Canyon Pil, Nv	40°17'	115°32'	8500

Ward Mountain #2 Pil, Nv	39°08'	114°49'	9200
Pole Creek RS, Pil, Nv	41°52'	115°15'	8330

Target Sites

Beaver Dams Pil	39°08'	111°33'	8000
Big Flat Pil	38°18'	112°21'	10290
Black Fl UM Creek Pil	38°41'	111°36'	9400
Box Creek Pil	38°30'	112°02'	9300
Buck Flat Pil	39°08'	111°27'	9800
Dill's Camp Pil	39°03'	111°27'	9200
Farnsworth Lake Pil	38°46'	111°40'	9600
Fish Lake Sc	38°33'	111°43'	8700
GBRC Alp Mead. Sc	39°18'	111°27'	10000
GBRC Headqts. Sc	39°19'	111°29'	8700
Gooseberry RS Pil	38°47'	111°41'	8400
Huntington Hrshoe Sc	39°37'	111°19'	9800
Kimberly Mine Pil	38°29'	112°23'	9300
Mammoth-Ctnwood Pil	39°41'	111°19'	8800
Mt. Baldy RS Sc	39°08'	111°30'	9500
Oak Creek SC	39°21'	112°21'	7760
Pickle Keg Spring Pil	39°02'	111°35'	9600
Pine Creek Pil	38°53'	112°15'	8800
Red Pine Ridge Pil	39°28'	111°16'	9200
Seeley Creek R.S. Pil	39°19'	111°26'	10000
Box Springs Pil*	38°30'	112°00'	9300
Thistle Flat Sc	39°14'	111°37'	8500
Upper Joes Valley Sc	39°26'	111°15'	8900

PRIMARY TARGET - SNOW COURSE AND SNOW PILLOW (continued)

Site	Lat(N)	Long(W)	Elev (Ft)
Wrigley Creek Sc	39°09'	111°20'	9000
Bryce Canyon Sc	37°38'	112°12'	8000
Castle Valley Pil	37°40'	112°44'	9500
Long Flat Pil	37°30'	113°25'	8000
Midway Valley Pil	37°34'	112°51'	9800
Tall Poles Sc	37°43'	112°51'	8800
Webster Flat Pil	37°59'	112°54'	9200
Widtsoe Esc. #3 Pil	37°50'	111°53'	9500
Yankee Res. Sc	37°32'	112°48'	8700

EASTERN TOOELE TARGET - SNOW COURSE AND SNOW PILLOW

Site	Lat(N)	Long(W)	Elev (Ft)
Control Sites			
Baker Creek #2, NV	38°58'	114°17'	8950
Bostetter RS, ID	42°10'	114°11'	7500
Corral Canyon, NV	40°17'	115°32'	8500
Murray Summit, NV	39°14'	114°58'	7250
Payson R.S., UT	39°56'	111°38'	8050
Target Sites			
Bevan's Cabin, UT	40°28'	112°15'	6450
Rocky Basin Settlement, UT	40°26'	112°13'	8900
Vernon Creek, UT	39°56'	112°25'	7500

APPENDIX D - EVALUATION RESULTS TABLES

Note: In the following analyses, the current season data are considered preliminary.

Primary Target Linear Regression
Dec-Mar Precipitation

YEAR	Control	Target	Predicted	Ratio	Increase
Regression (non-seeded) period:					
1957	9.6	12.7	13.1	0.97	-0.4
1958	10.3	13.9	14.3	0.98	-0.3
1959	6.6	8.8	7.9	1.11	0.9
1960	9.3	13.2	12.6	1.05	0.6
1961	6.6	8.5	8.0	1.06	0.5
1962	10.9	14.9	15.2	0.98	-0.3
1963	6.7	9.0	8.2	1.10	0.8
1964	6.9	8.4	8.4	1.00	0.0
1965	9.9	13.3	13.6	0.98	-0.3
1966	7.2	9.3	8.9	1.04	0.4
1967	9.5	12.0	12.8	0.94	-0.8
1968	9.3	12.9	12.6	1.03	0.3
1969	11.9	18.4	17.0	1.09	1.5
1970	8.0	10.6	10.4	1.02	0.2
1971	7.9	9.7	10.1	0.96	-0.4
1972	8.0	7.6	10.3	0.74	-2.7
1973	10.6	14.7	14.7	1.00	0.0
1984	10.6	14.8	14.6	1.01	0.1
Historical Mean	8.9	11.8	11.8	1.00	0.0
Seeded period:					
YEAR	Control	Target	Predicted	Ratio	Increase
1974	8.6	11.3	11.3	1.00	0.0
1975	9.1	12.8	12.1	1.06	0.7
1976	7.7	9.9	9.9	1.01	0.1
1977	4.6	6.4	4.6	1.40	1.8
1978	13.0	20.3	18.7	1.08	1.6
1979	10.5	16.3	14.5	1.12	1.8
1980	11.8	20.5	16.7	1.23	3.9
1981	6.6	9.3	8.0	1.16	1.3
1982	11.4	16.9	16.1	1.05	0.8
1983	10.8	17.5	15.0	1.17	2.5
1985*	7.0	11.3	8.6	1.31	2.7

YEAR	Control	Target	Predicted	Ratio	Increase
1986*	9.1	10.9	12.2	0.89	-1.3
1987*	6.6	9.7	8.0	1.21	1.7
1988	6.2	9.8	7.2	1.36	2.6
1989	8.0	10.2	10.3	0.99	-0.1
1990	6.5	9.1	7.8	1.17	1.3
1991	6.6	10.8	8.0	1.34	2.7
1992	6.4	10.2	7.6	1.34	2.6
1993	13.1	19.7	19.0	1.04	0.7
1994	5.7	8.7	6.5	1.35	2.3
1995	9.0	14.0	12.0	1.17	2.0
1996	9.1	12.9	12.2	1.05	0.7
1997	8.8	12.2	11.6	1.05	0.5
1998	9.4	14.4	12.6	1.14	1.8
1999	5.7	6.9	6.4	1.07	0.4
2000	8.3	12.4	10.8	1.15	1.7
2001	5.9	9.5	6.8	1.39	2.7
2002	5.9	6.2	6.7	0.92	-0.6
2003	5.8	9.6	6.6	1.45	3.0
2004	7.3	11.0	9.2	1.20	1.8
2005	10.3	15.9	14.2	1.13	1.8
2006	9.7	13.7	13.1	1.04	0.5
2007	6.3	7.2	7.4	0.98	-0.2
2008	8.8	15.1	11.7	1.28	3.3
2009	8.7	13.1	11.6	1.13	1.5
2010	8.4	13.8	11.1	1.24	2.7
2011	10.3	16.6	14.3	1.16	2.3
2012	6.6	8.7	7.9	1.09	0.7
2013	7.1	9.2	8.9	1.04	0.4
2014	6.1	7.9	7.1	1.10	0.7
2015	6.5	8.4	7.7	1.09	0.7
2016	8.8	11.4	11.7	0.98	-0.3
2017	12.6	16.1	18.0	0.89	-2.0
2018	6.1	8.5	7.2	1.18	1.3
2019	11.0	15.7	15.3	1.03	0.4
2020	8.0	10.1	10.4	0.98	-0.2
2021	6.8	9.3	8.4	1.12	1.0
Seeded Mean	8.3	12.0	10.8	**1.112**	**1.3**

*Seeding conducted in adjacent areas, but not target area

SUMMARY OUTPUT

Regression Statistics

YEAR		Control	Target	Predicted	Ratio	Increase
Multiple R	0.955721					
R Square	0.913403					

	Coefficients
Intercept	-3.173422
X Variable 1	1.688715

Eastern Tooele Target Linear Regression
Dec-Mar Precipitation

YEAR	Control	Target	Predicted	Ratio	Increase
Regression (non-seeded) period					
1957	13.3	10.6	10.9	0.97	-0.4
1958	16.7	11.7	13.9	0.84	-2.2
1959	10.5	8.4	8.4	0.99	-0.1
1960	13.8	11.2	11.4	0.98	-0.2
1961	9.2	6.7	7.3	0.92	-0.6
1962	15.8	11.6	13.2	0.88	-1.6
1963	10.6	7.7	8.6	0.89	-0.9
1964	11.4	7.8	9.3	0.84	-1.5
1965	16.4	12.0	13.6	0.88	-1.6
1966	10.5	7.4	8.5	0.87	-1.1
1967	16.1	10.1	13.4	0.75	-3.3
1968	15.2	10.7	12.6	0.85	-1.9
1969	20.6	17.7	17.3	1.02	0.4
1970	11.7	7.2	9.5	0.76	-2.3
1971	13.3	15.4	11.0	1.40	4.4
1972	11.2	7.6	9.1	0.84	-1.5
1973	18.2	20.1	15.2	1.32	4.9
1974	14.5	8.7	12.0	0.73	-3.3
1975	16.0	12.8	13.3	0.96	-0.5
1983	18.1	16.1	15.1	1.06	1.0
1984	18.7	13.7	15.6	0.88	-1.9
1985	11.0	11.6	8.9	1.29	2.6
1986	16.1	13.8	13.4	1.03	0.4
1987	10.6	11.2	8.6	1.30	2.6
1988	9.5	9.5	7.6	1.25	1.9
1993	16.9	17.3	14.1	1.23	3.3
1994	11.4	10.4	9.3	1.13	1.2
1995	15.3	14.8	12.6	1.17	2.2
Historical Mean	14.0	11.6	11.6	1.00	0.0

Seeded period:

YEAR	Control	Target	Predicted	Ratio	Increase

YEAR	Control	Target	Predicted	Ratio	Increase
1976	11.5	10.3	9.4	1.10	0.9
1977	8.6	6.6	6.9	0.96	-0.2
1978	19.4	20.7	16.3	1.27	4.4
1979	13.9	12.5	11.5	1.09	1.0
1980	18.8	19.6	15.8	1.24	3.8
1981	11.5	8.9	9.3	0.95	-0.5
1982	19.4	15.5	16.3	0.95	-0.8
1989	13.2	11.0	10.8	1.02	0.2
1990	9.6	9.8	7.7	1.27	2.1
1991	9.3	8.4	7.4	1.13	1.0
1992	9.2	7.4	7.4	1.01	0.1
1996	17.1	14.2	14.2	1.00	0.0
1997	15.5	15.0	12.9	1.16	2.1
1998	17.5	20.2	14.6	1.39	5.6
1999	10.9	9.3	8.8	1.05	0.5
2000	15.1	15.2	12.5	1.21	2.6
2001	10.3	9.4	8.3	1.12	1.0
2002	10.4	8.4	8.4	1.00	0.0
2003	9.5	8.7	7.6	1.14	1.1
2004	13.5	15.0	11.1	1.34	3.8
2005	16.1	15.4	13.4	1.15	2.0
2006	17.6	15.4	14.7	1.05	0.7
2007	10.3	9.9	8.3	1.19	1.6
2008	15.4	14.7	12.7	1.15	2.0
2009	15.9	13.6	13.2	1.03	0.4
2010	13.6	11.5	11.2	1.03	0.3
2011	17.9	16.6	14.9	1.11	1.6
2012	8.9	8.5	7.1	1.19	1.3
2013	10.3	9.5	8.3	1.15	1.2
2014	11.1	10.4	9.0	1.15	1.3
2015	7.7	6.2	6.0	1.03	0.2
2016	14.4	13.2	11.9	1.10	1.2
2017	20.0	18.8	16.8	1.12	2.0
2018	9.7	8.6	7.8	1.10	0.8
2019	18.9	17.3	15.5	1.11	1.5
2020	10.6	8.4	8.6	0.98	-0.2
2021	11.1	9.4	9.0	1.04	0.4
Seeded Mean	13.3	12.2	11.0	**1.12**	**1.3**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.782368
R Square	0.612099
Adjusted R Square	0.59718

YEAR	Control	Target	Predicted	Ratio	Increase
Standard Error	2.231851				
Observations	28				

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-0.69476	1.959753	-0.354514	0.725813	-4.72309
X Variable 1	0.875061	0.136616	6.405266	8.73E-07	0.594243

Primary Target
Apr 1 Snow Water Content

YEAR	Control	Target	Predicted	Ratio	Increase
Regression (non-seeded) period:					
1956	14.9	12.3	15.1	0.82	-2.7
1957	15.3	16.9	15.4	1.10	1.5
1958	20.2	20.6	20.5	1.00	0.1
1959	9.6	10.4	9.6	1.09	0.8
1960	12.4	13.9	12.5	1.11	1.4
1961	12.7	11.3	12.7	0.89	-1.4
1962	20.3	20.1	20.6	0.98	-0.5
1963	8.9	10.3	8.8	1.17	1.5
1964	12.0	11.4	12.1	0.95	-0.7
1965	16.2	17.9	16.4	1.09	1.5
1966	11.2	10.5	11.2	0.93	-0.7
1967	11.5	10.8	11.5	0.94	-0.7
1968	13.5	16.8	13.6	1.24	3.3
1969	21.0	23.1	21.4	1.08	1.7
1970	14.3	15.2	14.4	1.06	0.8
1971	14.9	14.4	15.1	0.96	-0.6
1972	12.2	8.4	12.3	0.69	-3.9
1973	21.6	20.7	21.9	0.94	-1.2
1984	23.8	24.1	24.2	0.99	-0.2
Historical Mean	15.1	15.2	15.2	1.00	0.0
YEAR	Control	Target	Predicted	Ratio	Increase
1974	13.9	15.6	14.0	1.11	1.6
1975	18.0	17.3	18.3	0.95	-1.0
1976	12.7	12.9	12.8	1.01	0.2
1977	8.1	8.2	8.0	1.02	0.2
1978	18.6	21.8	18.9	1.15	2.9
1979	18.0	21.4	18.2	1.17	3.2

YEAR	Control	Target	Predicted	Ratio	Increase
1980	19.3	23.6	19.6	1.20	4.0
1981	9.6	10.2	9.6	1.06	0.6
1982	20.3	20.5	20.7	0.99	-0.2
1983	23.1	26.0	23.6	1.10	2.4
1985*	16.3	16.5	16.5	1.00	0.0
1986*	13.8	15.7	13.9	1.13	1.8
1987*	11.2	13.0	11.2	1.17	1.9
1988	10.5	13.1	10.5	1.25	2.7
1989	14.5	11.3	14.6	0.77	-3.4
1990	9.2	10.5	9.1	1.16	1.4
1991	12.3	12.8	12.3	1.04	0.5
1992	11.7	12.1	11.7	1.04	0.4
1993	20.1	21.3	20.4	1.04	0.9
1994	9.3	10.8	9.3	1.17	1.6
1995	17.8	16.6	18.0	0.92	-1.4
1996	13.7	14.6	13.8	1.06	0.8
1997	15.5	15.1	15.7	0.96	-0.6
1998	17.1	16.7	17.4	0.96	-0.7
1999	10.3	8.1	10.3	0.79	-2.2
2000	12.8	13.7	12.9	1.06	0.8
2001	10.8	11.3	10.8	1.04	0.5
2002	10.4	9.6	10.4	0.92	-0.8
2003	9.5	12.1	9.5	1.28	2.6
2004	9.3	10.2	9.2	1.11	1.0
2005	20.8	20.1	21.1	0.95	-1.0
2006	16.7	17.4	16.9	1.03	0.5
2007**	7.9	6.8	7.8	0.87	-1.0
2008	15.1	16.1	15.2	1.06	0.8
2009	12.9	12.7	13.0	0.98	-0.2
2010	14.7	15.1	14.8	1.02	0.3
2011	16.0	20.1	16.2	1.24	3.9
2012**	7.3	7.9	7.1	1.11	0.8
2013	8.9	9.3	8.8	1.06	0.5
2014	9.5	9.9	9.4	1.05	0.5
2015**	5.0	6.1	4.7	1.28	1.3
2016	14.2	12.8	14.4	0.89	-1.5
2017**	16.4	13.9	16.6	0.84	-2.7
2018	8.2	7.9	8.1	0.97	-0.2
2019	18.7	19.5	18.9	1.03	0.6
2020	11.5	14.0	11.6	1.21	2.4
2021	10.9	11.0	10.9	1.00	0.1
Seeded Mean	13.9	14.6	14.0	**1.04**	**0.6**

* Seeding conducted in adjacent areas but not target area
** Results not included in average due to early snowmelt

YEAR	Control	Target	Predicted	Ratio	Increase

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9355563
R Square	0.8752657
Adjusted R Square	0.8679284
Standard Error	1.7407636
Observations	19

	Coefficients
Intercept	-0.37896640
X Variable	1.03556085

Primary Target

Apr 1 Snow Water Content Multiple Regression with Two Control Groups (North, South)

YEAR	North Ctrl	South Ctrl	Target	Predicted	Ratio	Increase
Regression period:						
1956	20.5	9.3	12.3	14.5	0.85	-2.2
1957	16.8	13.7	16.9	15.9	1.06	1.0
1958	25.5	14.9	20.6	20.3	1.02	0.3
1959	12.3	6.9	10.4	9.5	1.10	0.9
1960	13.7	11.2	13.9	12.9	1.08	1.0
1961	17.6	7.7	11.3	12.3	0.93	-0.9
1962	22.8	17.7	20.1	21.1	0.96	-0.9
1963	10.2	7.6	10.3	9.1	1.14	1.2
1964	17.1	6.9	11.4	11.5	0.99	-0.1
1965	20.0	12.4	17.9	16.4	1.09	1.5
1966	11.1	11.3	10.5	11.9	0.88	-1.4
1967	14.4	8.5	10.8	11.4	0.94	-0.7
1968	12.6	14.3	16.8	14.6	1.16	2.3
1969	21.1	21.0	23.1	22.5	1.03	0.6
1970	18.1	10.4	15.2	14.3	1.07	1.0
1971	21.0	8.9	14.4	14.4	1.00	0.0
1972	19.1	5.4	8.4	11.3	0.75	-2.9
1973	20.9	22.3	20.7	23.3	0.89	-2.6
1984	36.7	10.9	24.1	22.3	1.08	1.8

YEAR	North Ctrl	South Ctrl	Target	Predicted	Ratio	Increase
Historical Mean	18.5	11.6	15.2	15.2	1.00	0.0

YEAR	North Ctrl	South Ctrl	Target	Predicted	Ratio	Increase
Seeded Period:						
1974	20.9	7.0	15.6	13.1	1.19	2.5
1975	24.4	11.6	17.3	17.7	0.98	-0.4
1976	18.2	7.1	12.9	12.1	1.07	0.8
1977	9.9	6.3	8.2	8.1	1.01	0.1
1978	19.5	17.7	21.8	19.7	1.11	2.1
1979	19.0	17.0	21.4	19.0	1.13	2.4
1980	19.6	19.0	23.6	20.6	1.15	3.0
1981	10.1	9.1	10.2	10.1	1.01	0.1
1982	25.8	14.9	20.5	20.4	1.00	0.0
1983	24.6	21.6	26.0	24.4	1.06	1.6
1985*	17.8	14.9	16.5	17.1	0.97	-0.5
1986*	16.2	11.3	15.7	14.0	1.12	1.6
1987*	12.2	10.2	13.0	11.6	1.12	1.4
						2.8
1988	13.5	7.4	13.1	10.3	1.27	

YEAR	North Ctrl	South Ctrl	Target	Predicted	Ratio	Increase
1990	11.3	7.0	10.5	9.2	1.15	1.4
1991	12.7	11.9	12.8	13.0	0.99	-0.1
1992	10.0	13.3	12.1	12.8	0.95	-0.7
1993	17.2	22.9	21.3	22.2	0.96	-0.9
1994	9.9	8.7	10.8	9.7	1.12	1.1
1995	15.7	19.8	16.6	19.5	0.85	-2.9
1996	20.4	7.0	14.6	12.9	1.13	1.7
1997	19.7	11.3	15.1	15.5	0.97	-0.4
1998	18.3	15.9	16.7	18.0	0.93	-1.3
1999	14.8	5.7	8.1	9.7	0.83	-1.6
2000	16.0	9.6	13.7	12.8	1.07	0.9
2001	11.3	10.3	11.3	11.3	1.00	0.0
2002	15.8	5.0	9.6	9.7	0.99	-0.1
2003	10.1	8.9	12.1	9.9	1.22	2.2
2004	12.7	5.9	10.2	8.9	1.15	1.3
2005	18.4	23.1	20.1	22.8	0.88	-2.7
2006	23.9	9.4	17.4	16.0	1.09	1.4
2007**	11.2	4.5	6.8	7.4	0.91	-0.6
2008	17.7	12.5	16.1	15.4	1.04	0.6
2009	15.3	10.5	12.7	13.1	0.97	-0.4
2010	14.0	15.3	15.1	15.8	0.95	-0.7
2011	19.6	12.4	20.1	16.2	1.24	3.9

2012**	9.5	5.1	7.9	7.1	1.12	0.9
2013	12.0	5.8	9.3	8.6	1.08	0.7
2014	14.1	4.8	9.9	8.8	1.12	1.0
2015**	6.0	3.9	6.1	4.9	1.26	1.2
2016	21.0	7.4	12.8	13.5	0.95	-0.6
2017**	18.8	13.9	13.9	16.9	0.82	**-3.0**
2018	12.1	4.3	7.9	7.7	1.03	0.3
2019	21.9	15.4	19.5	19.2	1.02	0.4
2020	14.3	8.7	14.0	11.5	1.21	2.4
2021	15.4	6.4	11.0	10.4	1.05	0.5
Seeded Mean	16.5	11.2	14.6	14.1	**1.03**	**0.5**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.949996055
R Square	0.902492504
Coefficients	
Intercept	-0.260923565
X North	0.417766179
X South	0.666458753

Eastern Tooele Target
Apr 1 Snow Water Content

YEAR	Control	Target	Predicted	Ratio	Increase
Regression (non-seeded) period:					
1956	16.3	8.9	16.7	0.54	-7.7
1957	14.2	16.0	14.4	1.11	1.6
1958	20.9	16.2	21.6	0.75	-5.4
1959	10.6	10.2	10.5	0.97	-0.3
1960	12.0	16.2	12.0	1.35	4.2
1961	12.8	10.5	12.9	0.82	-2.3
1962	20.7	18.8	21.3	0.88	-2.5
1963	7.9	7.1	7.6	0.93	-0.5
1964	13.8	14.0	14.0	1.00	0.0
1965	17.0	16.3	17.4	0.93	-1.1
1966	11.1	9.4	11.1	0.85	-1.6
1967	12.7	11.9	12.7	0.93	-0.9
1968	12.5	14.0	12.6	1.12	1.4
1969	22.4	25.5	23.2	1.10	2.3
1970	14.7	11.9	14.9	0.79	-3.1

YEAR	Control	Target	Predicted	Ratio	Increase
1971	16.6	16.6	17.0	0.98	-0.4
1972	15.3	8.7	15.5	0.56	-6.9
1973	20.4	32.1	21.0	1.53	11.1
1974	17.2	13.1	17.6	0.74	-4.5
1975	18.1	20.1	18.6	1.08	1.5
1983	22.4	21.0	23.2	0.90	-2.2
1984	27.1	30.8	28.1	1.10	2.7
1985	15.0	20.3	15.2	1.33	5.1
1986	16.0	12.8	16.3	0.79	-3.5
1987	11.3	15.3	11.3	1.36	4.0
1988	11.7	12.2	11.7	1.05	0.6
1993	16.1	19.9	16.4	1.21	3.5
1994	10.0	11.5	9.9	1.16	1.6
1995	13.8	17.0	13.9	1.22	3.1
Historical Mean	15.5	15.8	15.8	1.00	0.0

Seeded period:

YEAR	Control	Target	Predicted	Ratio	Increase
1976	15.7	15.6	16.0	0.98	-0.4
1977	6.2	9.3	5.8	1.59	3.5
1978	17.4	21.1	17.8	1.18	3.3
1979	18.9	18.0	19.4	0.93	-1.4
1980	19.0	24.4	19.5	1.25	4.8
1981	9.3	12.5	9.2	1.36	3.3
1982	21.4	19.6	22.1	0.89	-2.5
1989	13.9	9.9	14.1	0.70	-4.2
1990	10.7	12.4	10.7	1.16	1.7
1991	10.2	10.5	10.1	1.05	0.5
1992	8.7	10.3	8.5	1.21	1.8
1996	14.5	12.8	14.7	0.87	-1.9
1997	14.8	17.9	15.0	1.19	2.9
1998	14.8	23.4	15.0	1.56	8.4
1999	10.1	8.8	10.0	0.88	-1.2
2000	11.2	15.9	11.2	1.42	4.7
2001	8.7	11.4	8.5	1.35	3.0
2002	11.2	11.0	11.2	0.98	-0.2
2003	8.5	9.6	8.3	1.16	1.3
2004	10.2	15.0	10.1	1.49	4.9
2005	18.0	20.2	18.5	1.09	1.7
2006	16.6	16.3	17.0	0.96	-0.6
2007*	6.8	7.2	6.4	1.11	0.7
2008	14.3	17.5	14.4	1.21	3.1
2009	12.6	13.9	12.6	1.10	1.2
2010	12.2	13.0	12.2	1.06	0.8
2011	16.0	21.9	16.3	1.34	5.5
2012*	8.2	7.2	7.9	0.91	-0.7

YEAR	Control	Target	Predicted	Ratio	Increase
2013	7.9	10.0	7.7	1.30	2.3
2014	10.1	8.3	9.9	0.83	-1.7
2015*	4.1	1.5	3.6	0.43	-2.0
2016	13.6	12.0	13.8	0.87	-1.8
2017*	12.9	13.8	13.0	1.06	0.8
2018	8.3	5.3	8.1	0.66	-2.8
2019	19.5	21.4	20.0	1.07	1.4
2020	10.7	11.5	10.7	1.08	0.8
2021	11.3	10.8	11.3	0.95	-0.5
Seeded Mean	12.9	14.3	13.0	**1.10**	**1.3**

* Not included in mean due to early-season snowmelt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.766963
R Square	0.588233
Adjusted R Square	0.572982
Standard Error	3.975414
Observations	29

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-0.80605	2.774503	-0.29052	0.773637	-6.49886
X Variable 1	1.068717	0.172081	6.210555	1.22E-06	0.715637

APPENDIX E - GLOSSARY OF RELEVANT METEOROLOGICAL TERMS

Advection: Movement of an air mass. Cold advection describes a colder air mass moving into the area, and warm advection is used to describe an incoming warmer air mass. Dry and moist advection can be used similarly.

Air Mass: A term used to describe a region of the atmosphere with certain defining characteristics. For example, a cold or warm air mass, or a wet or dry air mass. It is a fairly subjective term but is usually used in reference to large (synoptic scale) regions of the atmosphere, both near the surface and/or at mid and upper levels of the atmosphere.

Cold-core low: A typical mid-latitude type of low pressure system, where the core of the system is colder than its surroundings. This type of system is also defined by the cyclonic circulation being strongest in the upper levels of the atmosphere. The opposite is a warm-core low, which typically occurs in the tropics.

Cold Pool: An air mass that is cold relative to its surroundings, and may be confined to a particular basin

Condensation: Phase change of water vapor into liquid form. This can occur on the surface of objects (such as dew on the grass) or in mid-air (leading to the formation of clouds). Clouds are technically composed of water in liquid form, not water vapor.

Confluent: Wind vectors coming closer together in a two-dimensional frame of reference (opposite of diffluent). The term convergence is also used similarly.

Convective (or convection): Pertains to the development of precipitation areas due to the rising of warmer, moist air through the surrounding air mass. The warmth and moisture contained in a given air mass makes it lighter than colder, dryer air. Convection often leads to small-scale, locally heavy showers or thundershowers. The opposite precipitation type is known as stratiform precipitation.

Convergence: Refers to the converging of wind vectors at a given level of the atmosphere. Low-level convergence (along with upper-level divergence), for instance, is associated with lifting of the air mass which usually leads to development of clouds and precipitation. Low-level divergence (and upper-level convergence) is associated with atmospheric subsidence, which leads to drying and warming.

Deposition: A phase change where water vapor turns directly to solid form (ice). The opposite process is called sublimation.

Dew point: The temperature at which condensation occurs (or would occur) with a given amount of moisture in the air.

Diffluent: Wind vectors spreading further apart in a two-dimensional frame of reference; opposite of confluent

Entrain: Usually used in reference to the process of a given air mass being ingested into a storm system

Evaporation: Phase change of liquid water into water vapor. Water vapor is usually invisible to the eye.

El Nino: A reference to a particular phase of oceanic and atmospheric temperature and circulation patterns in the tropical Pacific, where the prevailing easterly trade winds weaken or dissipate. Often has an effect on mid-latitude patterns as well, such as increased precipitation in southern portions of the U.S. and decreased precipitation further north. The opposite phase is called La Nina.

Front (or frontal zone): Reference to a temperature boundary with either incoming colder air (cold front) or incoming warmer air (warm front); can sometimes be a reference to a stationary temperature boundary line (stationary front) or a more complex type known as an occluded front (where the temperature change across a boundary can vary in type at different elevations).

Glaciogenic: Ice-forming (aiding the process of nucleation); usually used in reference to cloud seeding nuclei

GMT (or UTC, or Z) time: Greenwich Mean Time, universal time zone corresponding to the time at Greenwich, England. Pacific Standard Time (PST) = GMT – 8 hours; Pacific Daylight Time (PDT) = GMT – 7 hours.

Graupel: A precipitation type that can be described as "soft hail", that develops due to riming (nucleation around a central core). It is composed of opaque (white) ice, not clear hard ice such as that contained in hailstones. It usually indicated the presence of convective clouds and can be associated with electrical charge separation and occasionally lightning activity.

High Pressure (or Ridge): Region of the atmosphere usually accompanied by dry and stable weather. Corresponds to a northward bulge of the jet stream on a weather map, and to an anti-cyclonic (clockwise) circulation pattern.

Inversion: Refers to a layer of the atmosphere in which the temperature increase with elevation

Jet Stream or Upper-Level Jet (sometimes referred to more generally as the storm track): A region of maximum wind speed, usually in the upper atmosphere that usually coincides with the main storm track in the mid-latitudes. This is the area that also typically corresponds to the greatest amount of mid-latitude synoptic-scale storm development.

La Nina: The opposite phase of that known as El Nino in the tropical Pacific. During La Nina the easterly tropical trade winds strengthen and can lead in turn to a strong mid-latitude storm track, which often brings wetter weather to northern portions of the U.S.

Longwave (or longwave pattern): The longer wavelengths, typically on the order of 1,000 – 2,000+ miles of the typical ridge/trough pattern around the northern (or southern) Hemisphere, typically most pronounced in the mid-latitudes.

Low-Level Jet: A zone of maximum wind speed in the lower atmosphere. Can be caused by geographical features or various weather patterns, and can influence storm behavior and dispersion of cloud seeding materials

Low-pressure (or trough): Region of the atmosphere usually associated with stormy weather. Corresponds to a southward dip to the jet stream on a weather map as well as a cyclonic (counter-clockwise) circulation pattern in the Northern Hemisphere.

Mesoscale: Sub - synoptic scale, about 100 miles or less; this is the size scale of more localized weather features (such as thunderstorms or mountain-induced weather processes).

Microphysics: Used in reference to composition and particle types in a cloud

MSL (Mean Sea Level): Elevation height reference in comparison to sea level

Negative (ly) tilted trough: A low-pressure trough where a portion is undercut, such that a frontal zone can be in a northwest to southeast orientation.

Nucleation: The process of supercooled water droplets in a cloud turning to ice. This is the process that is aided by cloud seeding. For purposes of cloud seeding, there are three possible types of cloud composition: Liquid (temperature above the freezing point), supercooled (below freezing but still in liquid form), and ice crystals.

Nuclei: Small particles that aid water droplet or ice particle formation in a cloud

Orographic: Terrain-induced weather processes, such as cloud or precipitation development on the upwind side of a mountain range. Orographic lift refers to the lifting of an air mass as it encounters a mountain range.

Pressure Heights:
(700 millibars, or mb): Corresponds to approximately 10,000 feet above sea level (MSL); 850 mb corresponds to about 5,000 feet MSL; and 500 mb corresponds to about 18,000 feet MSL. These are standard height levels that are occasionally referenced, with the 700-mb level most important regarding cloud-seeding potential in most of the western U.S.

Positive (ly) tilted trough: A normal U-shaped trough configuration, where an incoming cold front would generally be in a northeast– southwest orientation.

Reflectivity: The density of returned signal from a radar beam, which is typically bounced back due to interaction with precipitation particles (either frozen or liquid) in the atmosphere. The reflectivity depends on the size, number, and type of particles that the radar beam encounters

Ridge (or High Pressure System): Region of the atmosphere usually accompanied by dry and stable weather. Corresponds to a northward bulge of the jet stream on a weather map, and to an anti-cyclonic (clockwise) circulation pattern.

Ridge axis: The longitude band corresponding to the high point of a ridge

Rime (or rime ice): Ice buildup on an object (often on an existing precipitation particle) due to the freezing of supercooled water droplets.

Shortwave (or shortwave pattern): Smaller-scale wave features of the weather pattern typically seen at mid-latitudes, usually on the order of a few to several hundred miles; these often correspond to individual frontal systems

Silver iodide: A compound commonly used in cloud seeding because of the similarity of its molecular structure to that of an ice crystal. This structure helps in the process of nucleation, where supercooled cloud water changes to ice crystal form.

Storm Track (sometimes reference as the Jet Stream): A zone of maximum storm propagation and development, usually concentrated in the mid-latitudes.

Stratiform: Usually used in reference to precipitation, this implies a large area of precipitation that has a fairly uniform intensity except where influenced by terrain, etc. It is the result of larger-scale (synoptic scale) weather processes, as opposed to convective processes.

Sublimation: The phase change in which water in solid form (ice) turns directly into water vapor. The opposite process is deposition.

Subsidence: The process of a given air mass moving downward in elevation, such as often occurs on the downwind side of a mountain range

Supercooled: Liquid water (such as tiny cloud droplets) occurring at temperatures below the freezing point (32 F or 0 C).

Synoptic Scale: A scale of hundreds to perhaps 1,000+ miles, the size scale at which high and low pressure systems develop

Trough (or low pressure system): Region of the atmosphere usually associated with stormy weather. Corresponds to a southward dip to the jet stream on a weather map as well as a cyclonic (counter-clockwise) circulation pattern in the Northern Hemisphere.

Trough axis: The longitude band corresponding to the low point of a trough

Upper-Level Jet or Jet Stream (sometimes referred to more generally as the storm track): A region of maximum wind speed, usually in the upper atmosphere that usually coincides with the main storm track in the mid-latitudes. This is the area that also typically corresponds to the greatest amount of mid-latitude synoptic-scale storm development.

UTC (or GMT, or Z) time: Greenwich Mean Time, universal time zone corresponding to the time at Greenwich, England. Pacific Standard Time (PST) = GMT – 8 hours; Pacific Daylight Time (PDT) = GMT – 7 hours.

Vector: Term used to represent wind velocity (speed + direction) at a given point

Velocity: Describes speed of an object, often used in the description of wind intensities

Vertical Wind Profiler: Ground-based system that measures wind velocity at various levels above the site