Annual Cloud Seeding Report

Southern & Central Utah Program
2022-2023 Winter Season

Prepared For:

State of Utah, Division of Water Resources

Utah Water Resources Development Corporation

Lower Colorado River Basin States

Prepared By:

Todd Flanagan

Garrett Cammans

North American Weather Consultants, Inc.

8180 S. Highland Dr., Suite B-2

Sandy, Utah 84093

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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. The goal of the seeding program is to augment wintertime snowpack/precipitation over the seeded watersheds. Cost sharing for the seeding program is provided by the Utah Division of Water Resources, and additional funds from the Lower Colorado River Basin States has resulted in early-season (November 1st-15th) and late season (March 16th - April 15th) extensions to the seeding program since 2010.

Precipitation and snowfall were well above normal during the 2022-2023 winter season, with some locations approaching record totals for the winter season. A total of 3594.00 CNG hours were conducted during 21 storm periods for the core program this season. An additional 737.25 hours of seeding were conducted during three early-season storm periods and 908.00 hours of seeding were conducted during six late-season storm periods for the Lower Basin Extension periods. **Beginning on March 16 and continuing for the remainder of the season, any seeding that would affect the Virgin River Headwaters (e.g., Pine Valley Mountains, Cedar Breaks area in N/NW flow) were suspended due to excessive snowpack in this area which prompted concerns regarding potential snowmelt flooding.**

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 have suggested long-term seasonal increases averaging 13% for eastern Tooele County and 11% for the primary target areas of central and southern Utah. April 1st snowpack evaluations have suggested 10% increase in Eastern Tooele County and 4% increases for the central and southern Utah watersheds. As discussed in section 5.0 of the report, the precipitation evaluation results are strongest mathematically, and suggest a 1.2-1.5 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. Commitment to conduct a program each winter provides stability and acceptance by funding agencies and the general public. The program is designed so that it can be temporarily suspended or terminated during a given winter season, should snowpack accumulate to the point where additional water may not be beneficial.

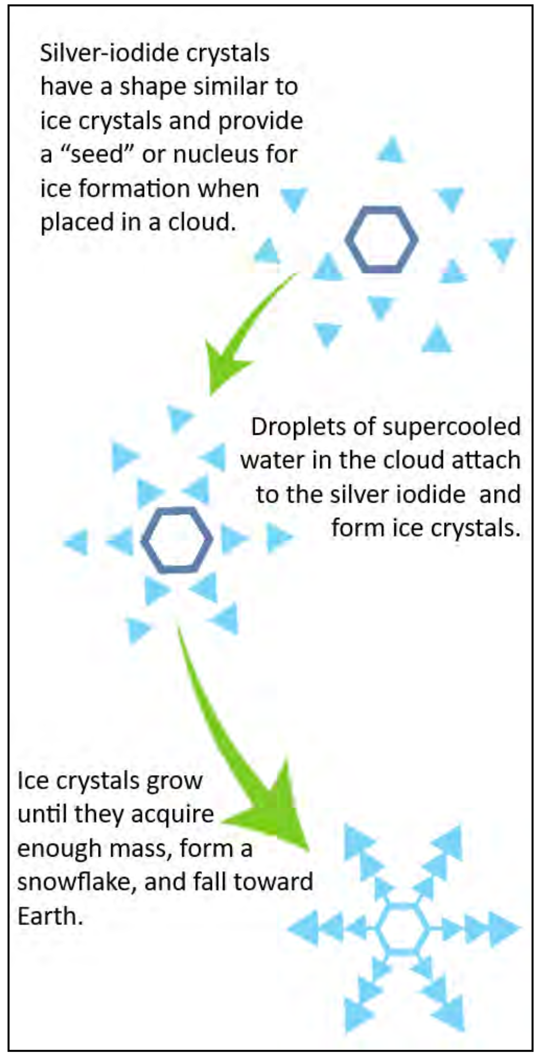
WEATHER MODIFICATION

The Science Behind Cloud Seeding

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.

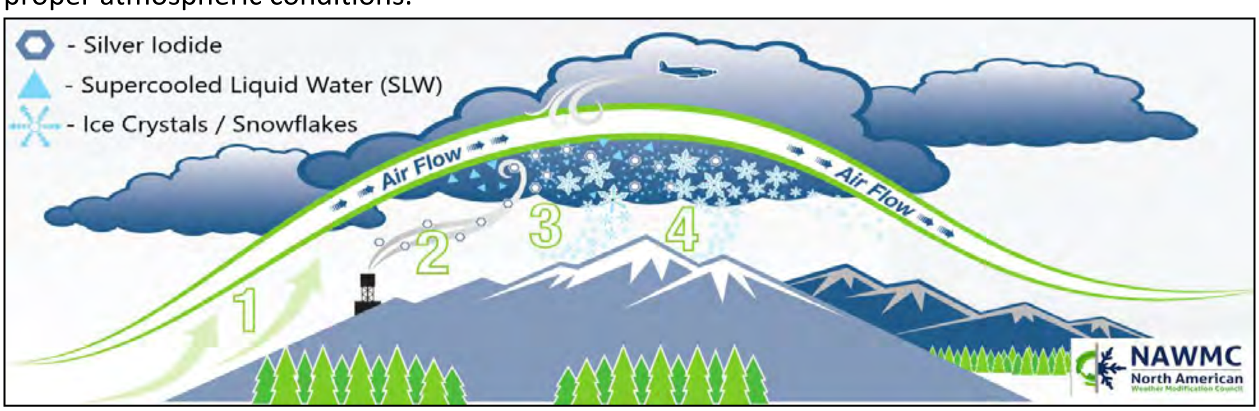


Safety

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 current 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.

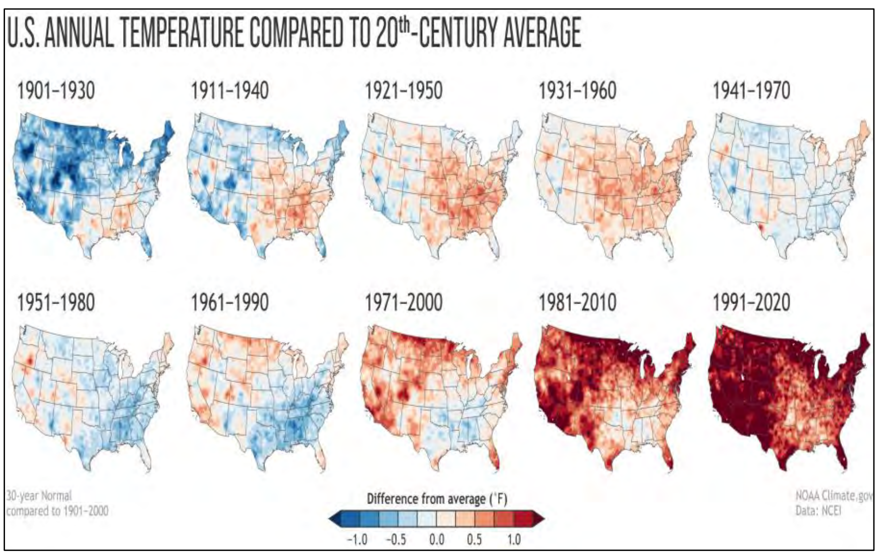


Figure 1. U.S. Annual Temperature compared to 20th-Century Average

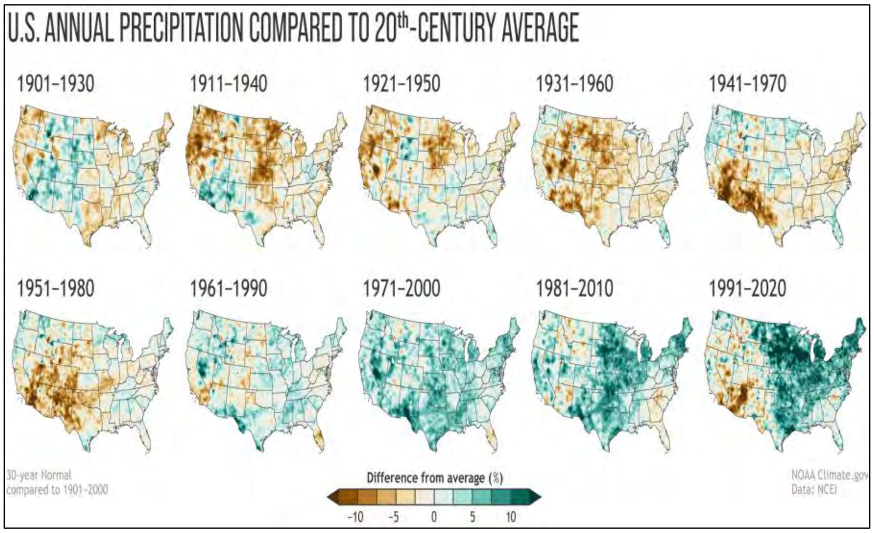


Figure 2. **U.S. Annual Precipitation compared to 20th-Century Average**

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.

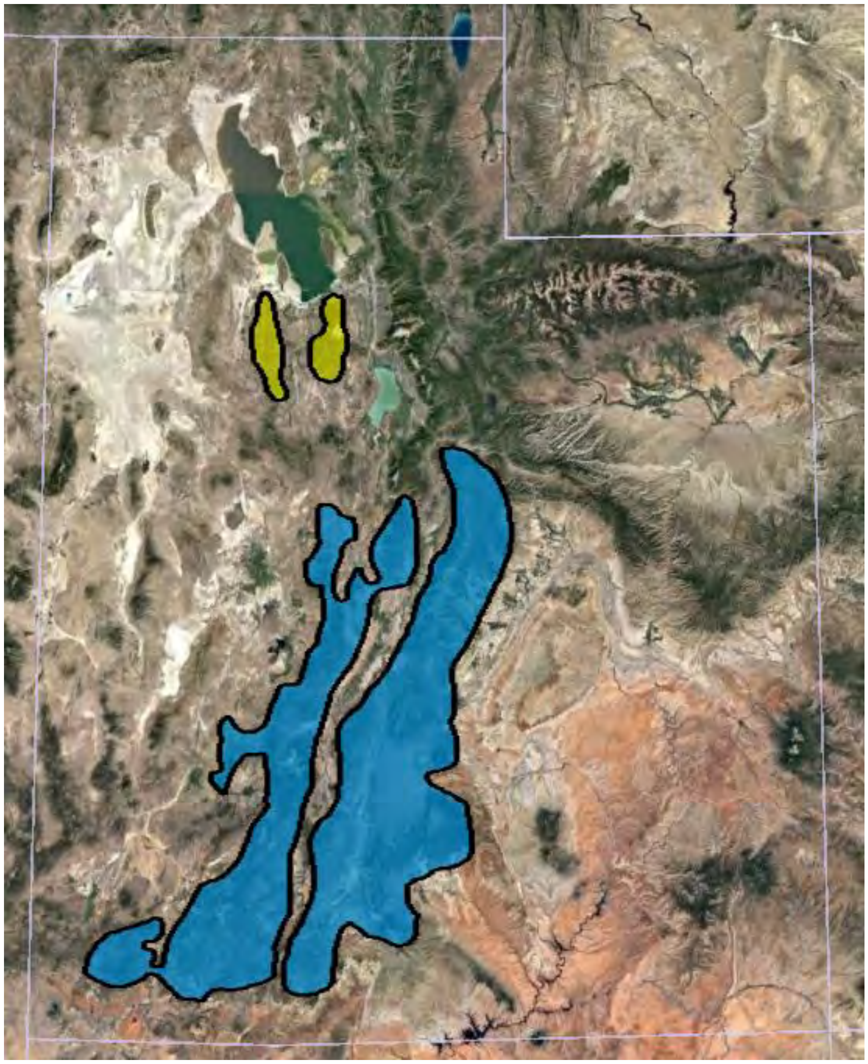


Figure 1.1. Seeded target areas in central and southwestern Utah; Eastern Tooele Target (yellow) and Primary Target (blue)

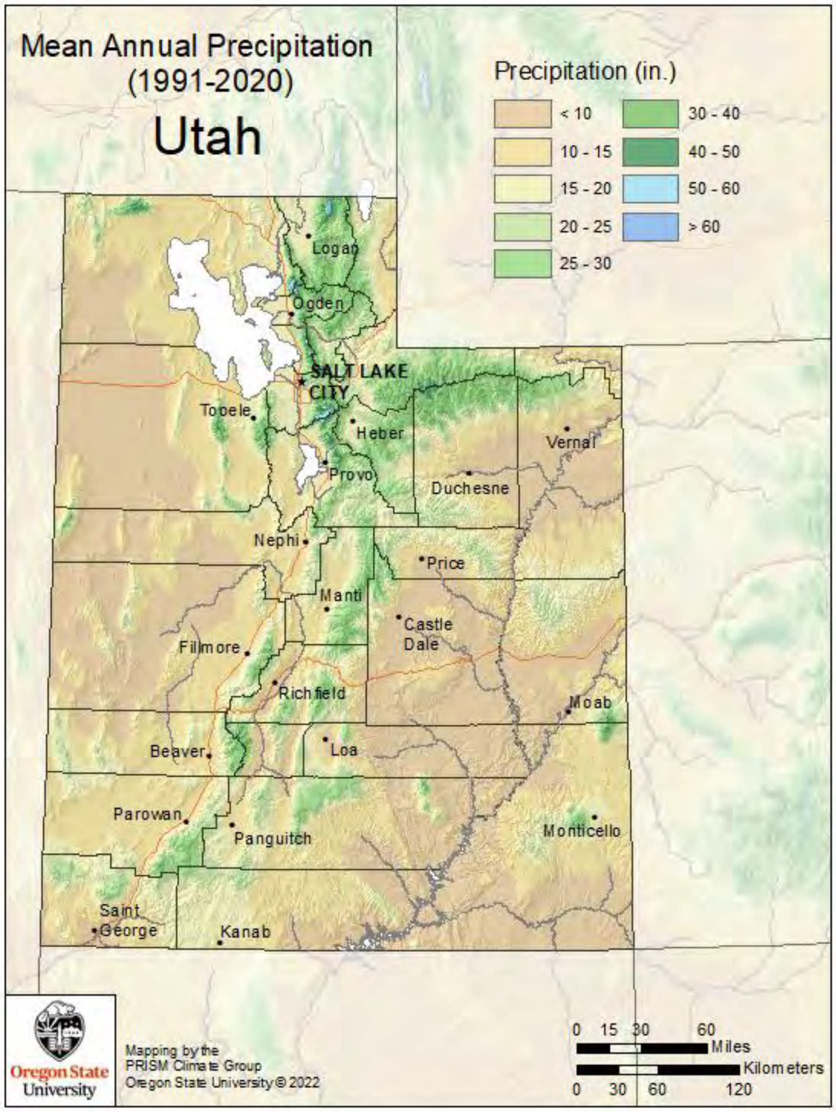


Figure 1.2, **Utah average annual precipitation**

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. The extension periods funded by the Lower Basin States and Utah's Division of Water Resources ran from November 1-15 and March 16 – April 15. One area was placed under suspension beginning on March 16, centered around the Virgin River headwaters region due to the excessive snowpack in the Pine Valley Mountains and Cedar Breaks region.

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 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 Skyline site in central Utah was discontinued prior to the start of the 2020-21 season due to reallocation of funding from the Lower Basin States. For the 2022-23 season, the Brian Head site became inoperable early in the season due to a power source failure.

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 methods and evaluation enhancements into the project when they are believed to be of practical value to the project.

2.2 Seedability Criteria

NAWC conducts selective seeding during winter storm events, which is the most efficient and cost-effective method. Selective seeding means that seeding is conducted only during specific time periods and in specific locations where it is likely to be effective. This decision is based on several criteria which determine the seedability of the storm. These criteria deal with characteristics of the atmosphere including temperature, stability, and wind flow, both in and below the clouds. Moisture content of the atmosphere, including cloud types and occurrence of supercooled liquid water (SLW) are important factors during seeding operations. Some heavier storm periods may not be seeded due to factors which make the storm naturally efficient at producing precipitation. Other storm periods can be deemed unfavorable due to several factors including temperature, stability or wind direction. The general criteria are provided below. The use of this focused seeding method has yielded consistently favorable results with very high cost/benefit ratios in a number of NAWC projects conducted in the western U.S.

- Cloud bases are below mountain barrier height.
- Low level wind speed and direction that would favor the transport of silver iodide seeding material, from its release locations into the target area.
- The absence of low level inversions or stable layers that would restrict the vertical movement of silver iodide from the surface to the -5°C level (23°F) or colder.
- Temperatures at the 700-mb level are warmer than -15°C (5°F)

2.3 Equipment and Project Set-Up

During the Fall of 2022, 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, 66 in all, are shown in Figure 2.1. Information on these locations is provided in Table 2-1.

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

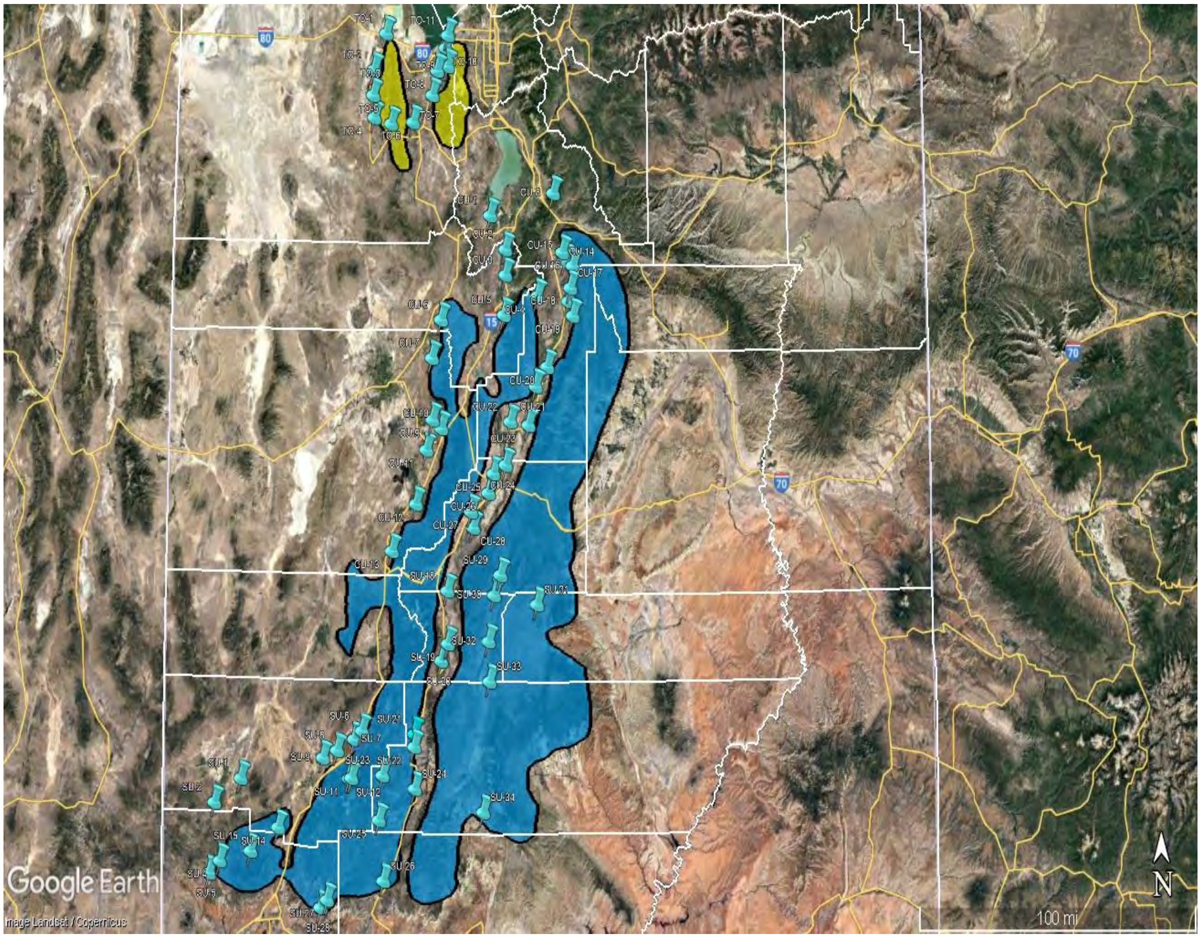


Figure 2.1. Target areas and seeding site location (primary target in blue and Tooele County in yellow)

Table 2-1
Seeding Site Locations

Site Number	Name	Latitude (N)	Longitude (W)	Elevation (feet)
TO-1	Skull Valley North	40°41.11'	112°40.10'	4289
TO-2	Skull Valley North/Central	40°32.20'	112°44.74'	4390
TO-3	Skull Valley Central #3	40°35.00’	112°41.00’	4300
TO-4	Skull Valley South #4	40°23.87’	112°42.92’	4890
TO-5	Terra	40°19.12'	112°37.60'	5166
TO-6	Rush Valley	40°19.50'	112°28.75'	5342
TO-7	Stockton	40°26.12'	112°21.18'	5234
TO-8	Settlement Canyon	40°31.14’	112°18.16’	5140
TO-9	Pine Canyon	40°33.09'	112°15.15'	5095
TO-10	Erda	40°37.50'	112°16.97'	4415
TO-11	Lakepoint	40°40.85’	112°15.85’	4250
CU-1	Elberta	39°57.12'	111°57.72'	4732
CU-2	Mona	39°48.93’	111°51.61’	4943
CU-3	Nephi West	39°42.78'	111°51.56'	5042
CU-4	Fountain Green	39°37.69'	111°38.88'	5985
CU-5	Levan	39°33.17'	111°52.06'	5286
CU-6	Leamington	39°31.99'	112°16.92'	4721
CU-7	Oak City	39°22.76'	112°20.43'	5059
CU-8	Spanish Fork	40° 2.000'	111° 33.00'	5230
CU-9	McCornick	39°07.95'	112°20.01'	4848
CU-10	Holden	39°05.92'	112°16.49'	5077
CU-11	Fillmore	39°00.71’	112°22.30’	4879
CU-12	Kanosh	38°47.71'	112°26.20'	5048
CU-13	Cove Fort	38°36.35'	112°35.44'	5942
CU-14	Birdseye	39°55.70'	111°34.08'	5600
CU-15	Hideaway Valley	39°46.32'	111°27.90'	6300
CU-16	Milburn	39°44.88'	111°24.96'	6787
CU-17	Fairview	39°39.61’	111°25.87’	6125
CU-18	Fairview South	39°36.44'	111°26.71	5855
CU-19	Mt. Pleasant	39°32.46'	111°27.03'	5981
CU-20	Ephraim	39°20.73'	111°34.95'	5626
CU-21	Manti	39°16.08'	111°39.51'	5505
CU-22	Centerfield	39°07.60'	111°49.43'	5100
CU-23	Mayfield	39°06.97'	111°42.52'	5550
CU-24	Salina	38°57.22'	111°51.21'	5190
CU-25	Aurora	38° 55.83’	111° 55.58’	5176
CU-26	Sigurd	38°50.52’	111°57.90’	5220
CU-27	Richfield	38°45.96’	112°04.68’	5296
CU-28	Annabella	38°42.17'	112°03.77'	5316

Site Number	Name	Latitude (N)	Longitude (W)	Elevation (feet)
SU-1	Newcastle	37°40.61'	113°33.73'	5242
SU-2	Enterprise	37°34.50'	113°43.99'	5345
SU-4	Veyo	37° 20.17'	113° 41.42'	4487
SU-5	Gunlock	37°17.16'	113°45.88'	3638
SU-6	Paragonah	37°52.98’	112°46.56’	5880
SU-7	Parowan	37°50.88'	112°49.56'	5980
SU-8	Summit	37°48.04'	112°55.96'	6009
SU-9	Enoch	37°46.44'	113°01.55'	5566
SU-11	Brian Head Summit	37°41.64'	112°50.76'	9591
SU-12	Brian Head Store	37°41.58'	112°51.00'	9700
SU-14	New Harmony	37°29.05'	113°18.85'	5355
SU-15	Pine Valley	37°23.05'	113°29.57'	6579
SU-18	Marysvale	38°26.98'	112°13.72'	5870
SU-19	Kingston	38°12.40'	112°11.33'	6018
SU-20	Circleville	38°10.27'	112°16.03'	6082
SU-21	Spry	37°52.43'	112°26.24'	6564
SU-22	Panguitch	37°52.38'	112°23.88'	6610
SU-23	Panguitch Lake	37°42.39’	112°38.47’	8255
SU-25	Duck Creek	37°31.50’	112°39.80’	8451
SU-27	Springdale	37°11.65'	112°59.83'	3987
SU-28	Rockville	37°09.70'	113°02.35'	3737
SU-29	Koosharem	38°30.87'	111°53.13'	6973
SU-30	Greenwich	38°26.00’	111°55.54’	6882
SU-31	Loa	38°23.83'	111°38.89'	7052
SU-32	Angle	38°14.91'	111°57.65'	6415
SU-33	Antimony	38°05.29'	111°57.25'	6661
SU-34	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 55 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 2022-2023 cloud seeding program for central and southern Utah began on November 15, 2022, and ended on March 15, 2023. The extension periods funded by the Lower Basin States and Utah's Division of Water Resources, ran from November 1-15 and March 16 – April 15. 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. Due to excessive snowpack and the threat of significant flooding with the spring melt, a suspension area was hoisted beginning March 16, with all seeding operations potentially affecting the Virgin River headwaters, including the Pine Valley Mountains and Cedar Breaks region placed on suspension. 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.

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

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. For the 2022-23 season, one significant suspension area was created in southwest Utah. By mid-March, snowpack in southwest Utah was in excess of 250 percent of normal, and there were growing concerns about the potential for significant snowmelt flooding along the Virgin River; for this reason, all seeding operations that would affect the Virgin River headwaters, essentially the Pine Valley Mountains and the Cedar Breaks region, were suspended for the remainder of the season.

3.0 WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

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 (weather balloon) upper-air observations, satellite images, radar information and weather cameras. NAWC's meteorologists have access to all meteorological products from their homes, allowing continued monitoring and conduct of seeding operations outside of regular business hours. This wide variety of available products and information helps NAWC meteorologists to determine when conditions are appropriate for cloud seeding.

Figures 3.1 – 3.4 show examples of some of the available weather information that was used in this decision-making process during the 2022-23 winter season. These include weather radar images, satellite images, surface wind and temperature maps, rawinsonde/weather balloon soundings and aviation hazards. Global and regional forecast models are a cornerstone of modern weather forecasting, and an important tool for operational meteorologists. These 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 display is shown from the Global Forecast System **(GFS)** model (Figure 3.5). Other models used on a daily basis during the program include but are not limited to the European Center for Medium-Range Weather Forecast **(ECMWF)** model, High-Resolution Rapid Refresh **(HRRR)** model, and North American Model **(NAM)**.

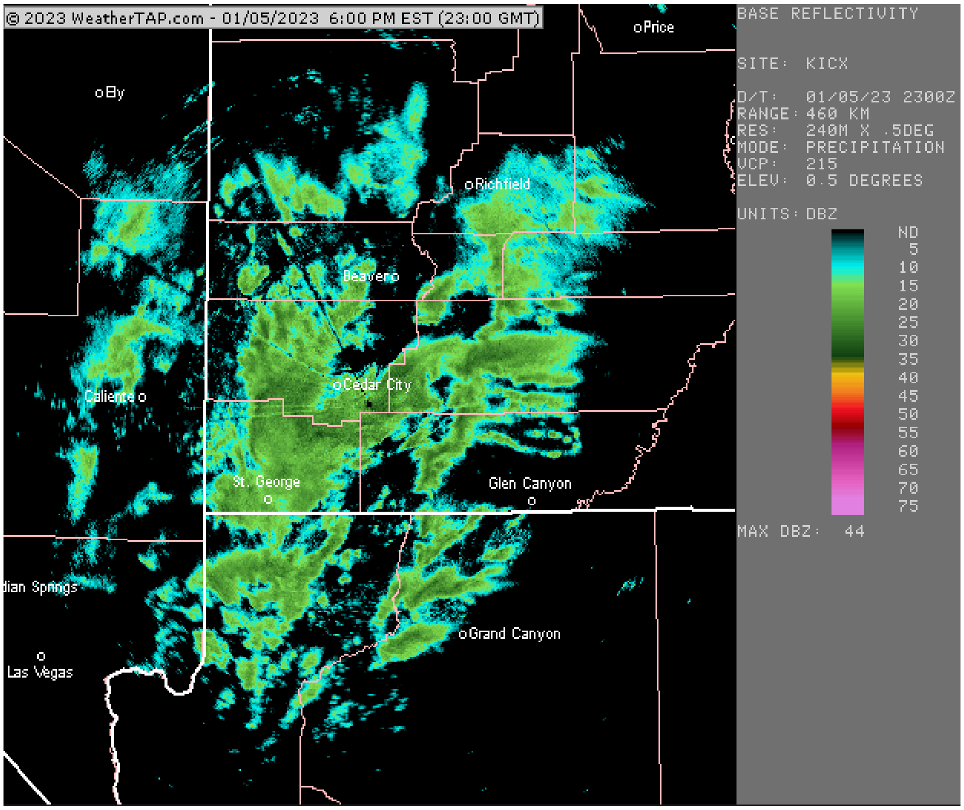


Figure 3.1. **Weather radar image from Cedar City during a storm event over southern Utah on January 5, 2023.**

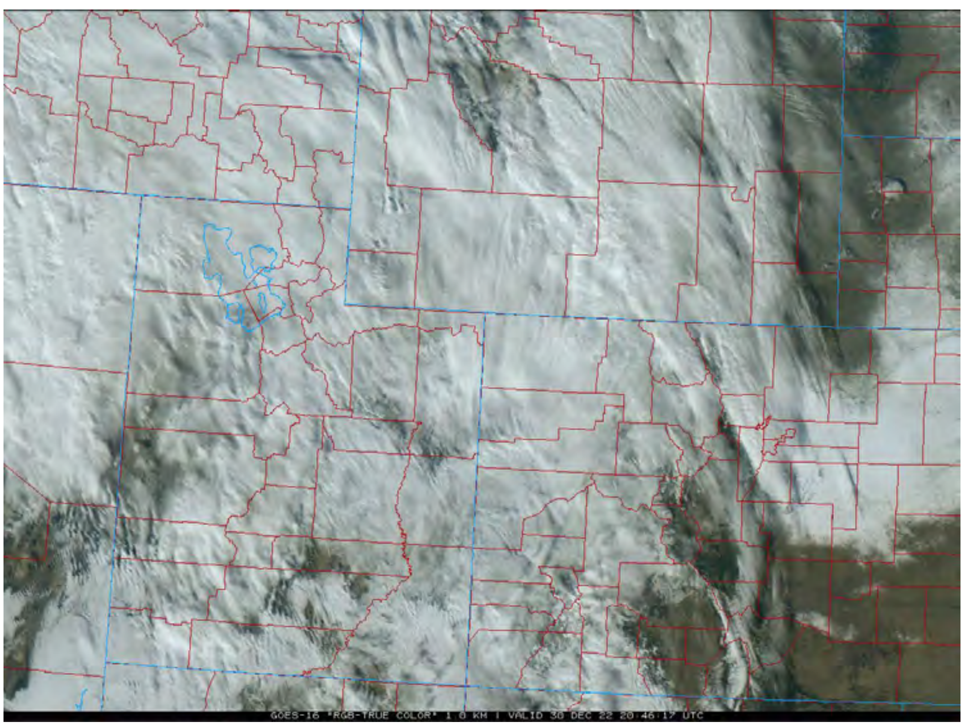


Figure 3.2. **Visible spectrum satellite image on December 30, 2022.**

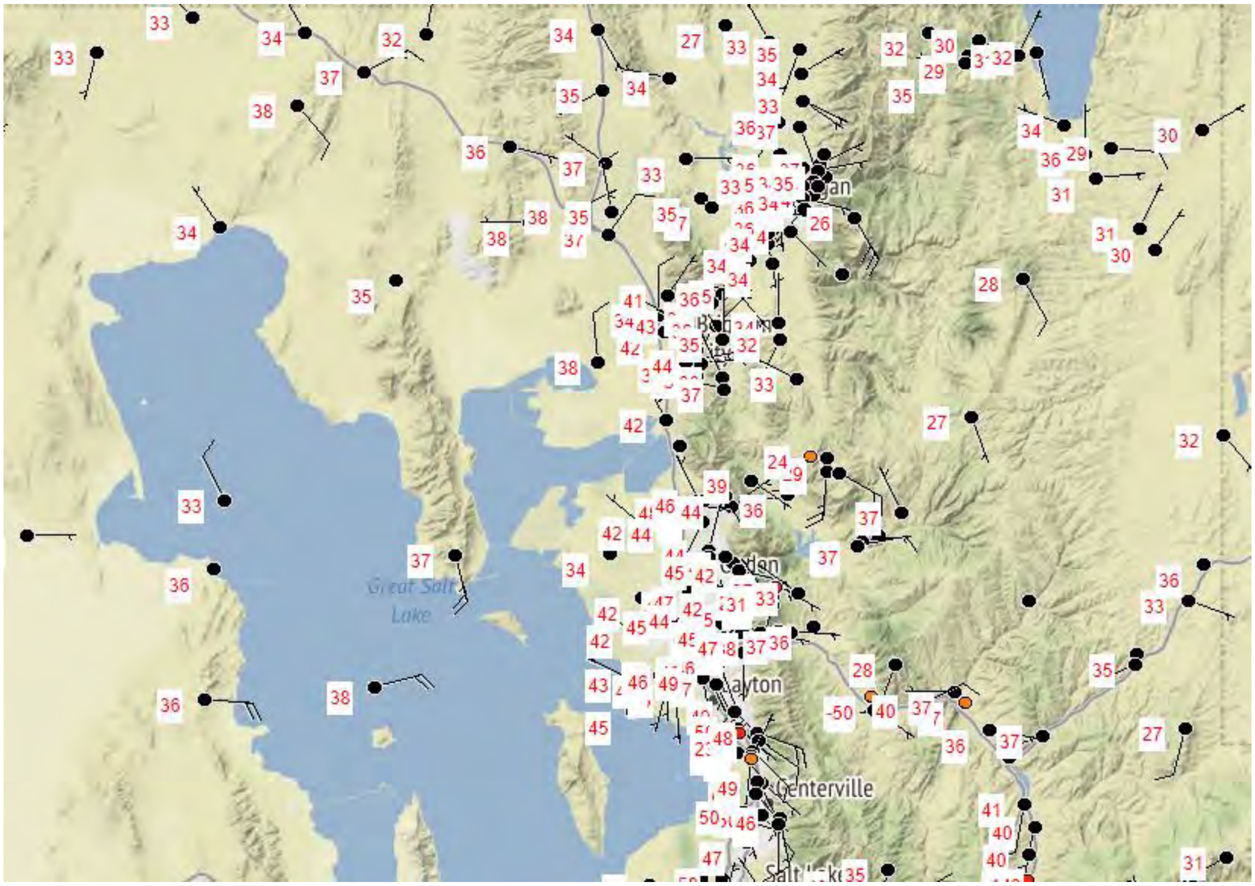


Figure 3.3. **MesoWest surface data map on January 10, 2023. Surface observations are important for diagnosing low level wind patterns and mixing.**

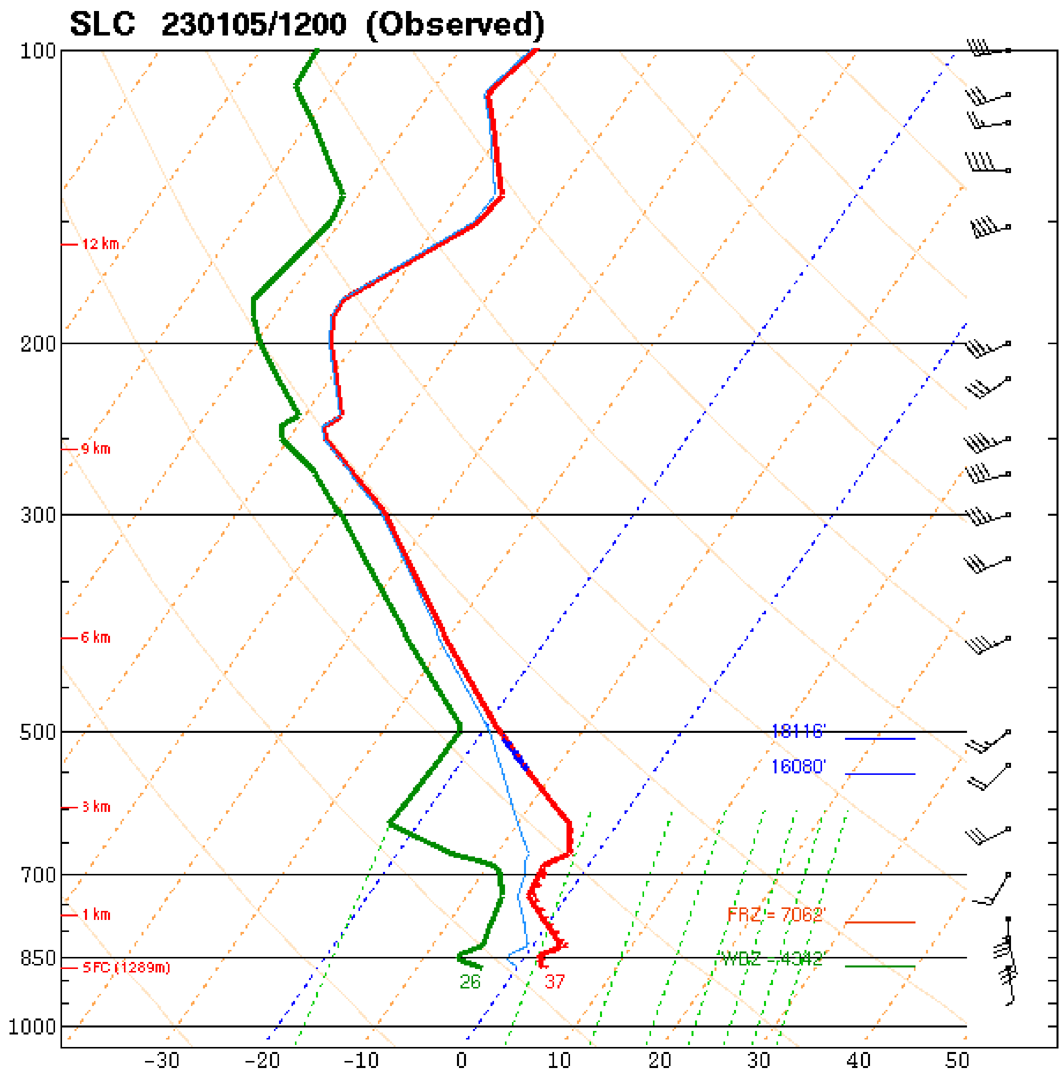


Figure 3.4. Weather balloon/rawinsonde sounding from Salt Lake City, valid at 12Z/0500 MST on January 5, 2023 showing temperature (red line), dewpoint (green line) and wind speed/direction (right side barbs) from the surface to 100 mb (approximately 52,000 feet MSL).

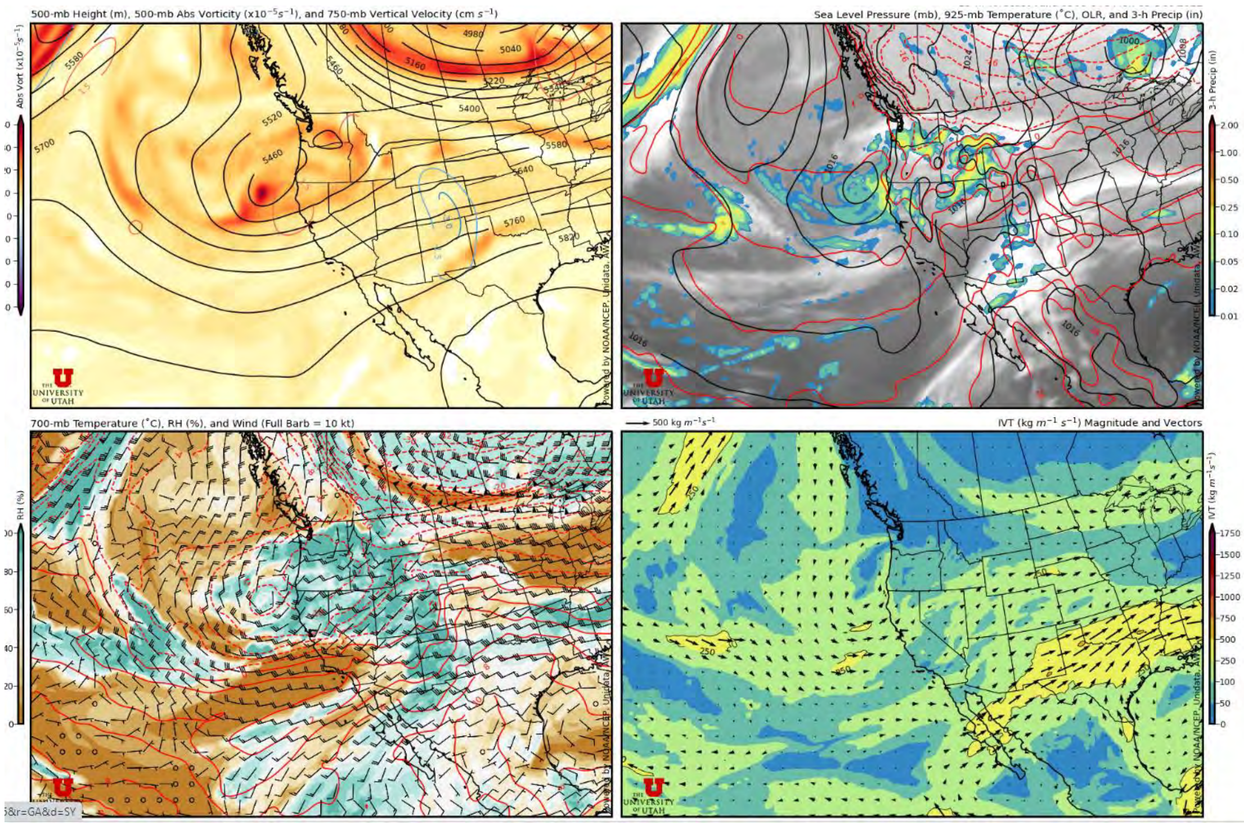


Figure 3.5. **GFS (Global Forecast Systems) model forecast (4-panel plot) during a storm event on December 4, 2022.**

Figure 3.6 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.

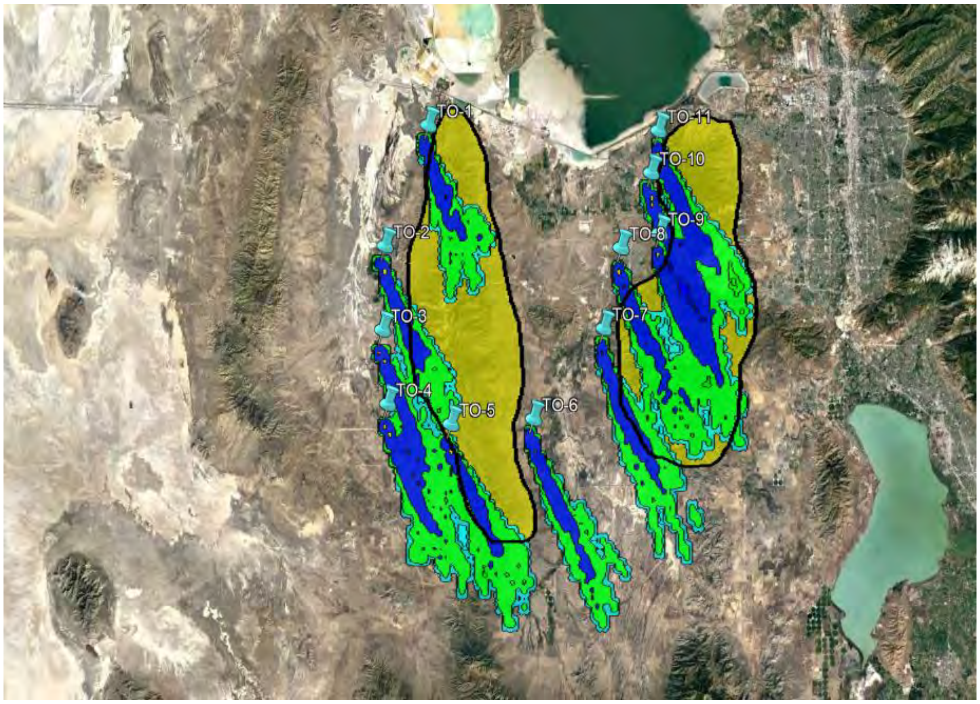


Figure 3.6. **HYSPLIT plume dispersion forecast from a seeding storm event on February 21, 2022, for the Tooele County target areas. This shows short term (less than 1 hour) plume dispersion forecasts for available seeding sites.**

4.0 OPERATIONS

A total of 21 storm events were seeded during the main core program contract period (November 15th – March 15th), three events were seeded during the early Lower Basin extension period (November 1-15) and six events were seeded during the latter extension period (March 15-April 15). In all, there were four seeded storm events in November, four events in December, seven in January, seven in February, seven in March, and one in April. For the regular contract period, a cumulative 3594.00 generator hours were utilized. For the Lower Basin extension, there was an additional 737.25 generator hours of seeding conducted in the November 1-15 period, and 896.00 generator hours of seeding during the March 15-April 15 period, totaling 1633.25 hours of seeding for the entire extension period. Figure 4.1 shows cumulative seeding hours for the core program this season with the special core program extension period of March 16 – April 30 included. 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.

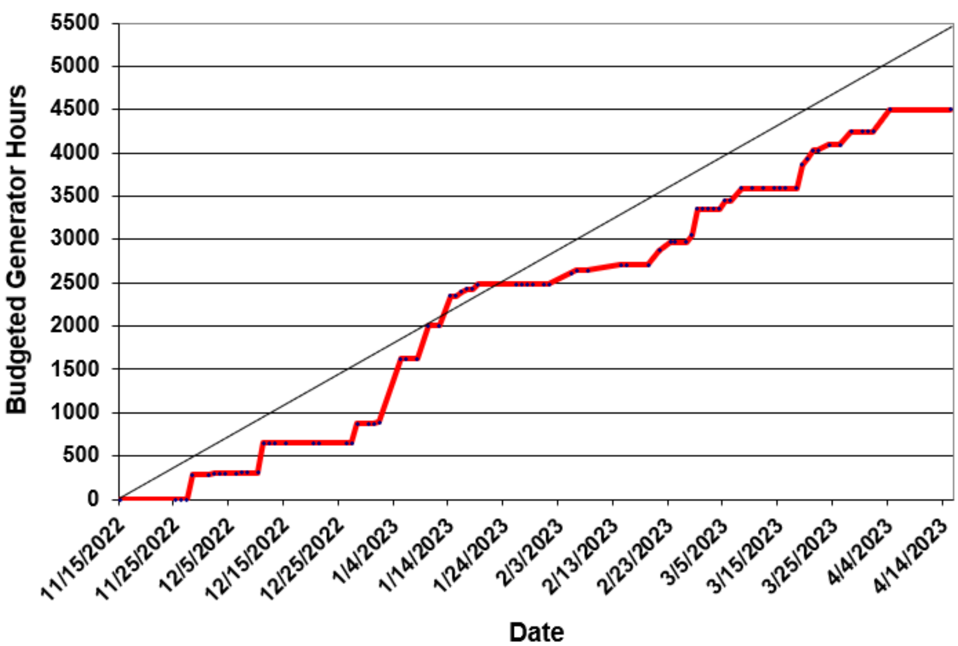


Figure 4.1. **Cumulative and budgeted seeding hours for the southern/central Utah core program and core program extension during the 2022-23 season. Red line shows actual usage this season, while the black diagonal line depicts a linear usage of budgeted hours.**

Table 4-1
Storm dates and generator usage, 2022-2023 season

Storm No.	Date(s)	Number of CNG Sites	Number of Generator Hours		
			Primary Contract	Lower Basin Extension	Total Hours
1	November 2-3	26		531.00	531.00
2	November 9	22		201.25	201.25
3	November 13	1		5.00	5.00
4	November 28-29	22	283.00		283.00
5	December 2	4	14.00		14.00
6	December 7	2	6.75		6.75
7	December 11-12	31	349.25		349.25
8	December 27-28	31	216.75		216.75
9	January 1	1	18.75		18.75
10	January 5-6	40	731.50		731.50
11	January 9-11	28	384.00		384.00
12	January 14-15	17	344.75		344.75
13	January 16	9	43.50		43.50
14	January 17	8	33.50		33.50
15	January 19-20	4	57.00		57.00
16	February 5	23	129.00		129.00
17	February 6	7	32.75		32.75
18	February 14	12	64.50		64.50
19	February 21-22	9	168.00		168.00
20	February 23-24	6	96.00		96.00
21	February 27-28	6	76.75		76.75
22	February 28-March 1	15	304.50		304.50
23	March 5-6	8	93.00		93.00
24	March 8	24	146.75		146.75
25	March 19-20	19		270.75	270.75
26	March 20	8		57.75	57.75
27	March 21-22	6		91.00	91.00
28	March 24	10		65.75	65.75
29	March 29-30	20		150.75	150.75
30	April 3-4	14		260.00	260.00
Total Hours			**3594.00**	**1633.25**	**5227.25**

As of April 1st, 2023, SNOTEL observations were indicative of a very busy season. All basins throughout the state were well above median snowfall and precipitation since October 1 was above mean values for all areas. It is worth noting that snowpack (SWE) percentages were significantly higher than water year precipitation percentages. The primary reason for this is that a larger than usual proportion of the precipitation since October 1 was in the form of snowfall, with very little melting; also, there may have been gauge catch problems, leading to cumulative precipitation numbers biased toward the low side at some sites. The April 1 data are summarized in Table 4-2.

Table 4-2
Snowpack and Precipitation Percentages on April 1, 2023

River Basin	No. of Reporting Stations	Snow Water Percent of Median	Water Year Precipitation Percent of Average
Tooele County	4	196%	167%
Price - San Rafael	9	206%	169%
Beaver River	3	190%	169%
Upper Sevier River	19	214%	158%
Southwestern Utah	12	293%	189%

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, 2022 – May 31, 2023 snow water equivalent and normal values for three SNOTEL sites.

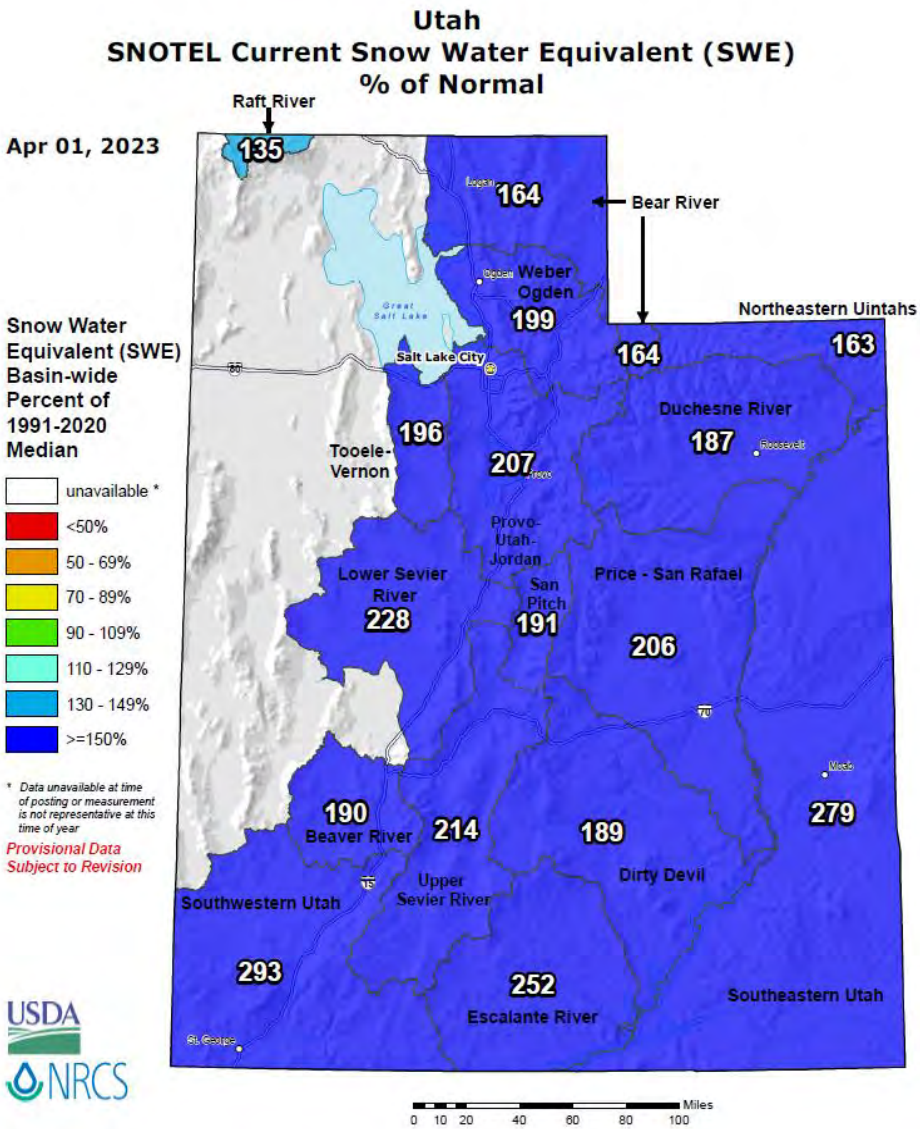


Figure 4.2. **Snow water content in Utah on April 1st, 2023 (percent of median)**

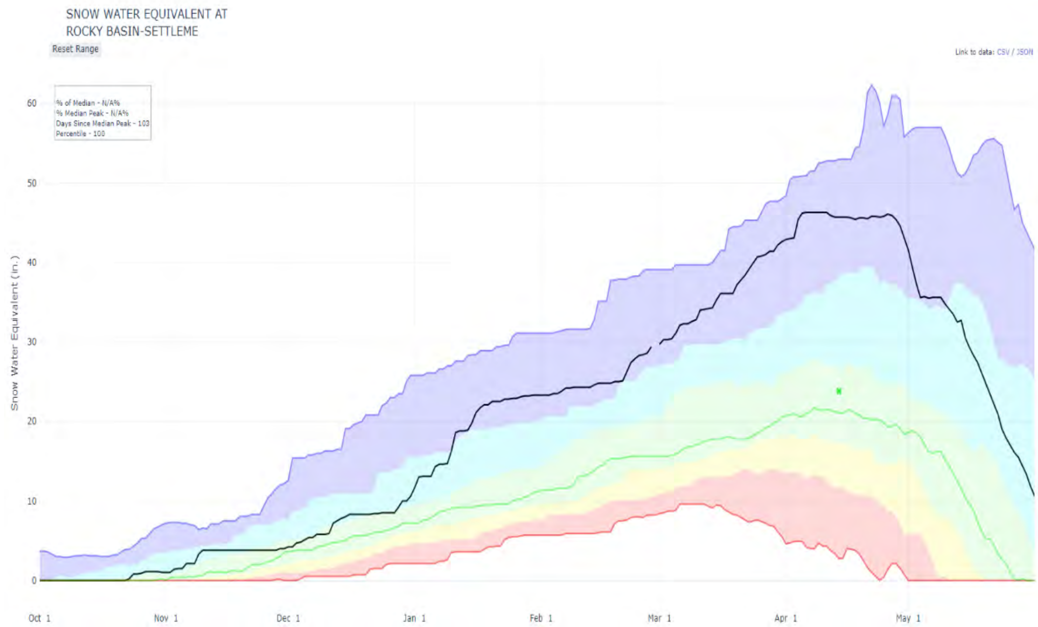


Figure 4.3. **NRCS SNOTEL snow water content plot for October 2022 through May 2023 for Rocky Basin-Settlement Tooele County. Black line is the 2022-23 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.**

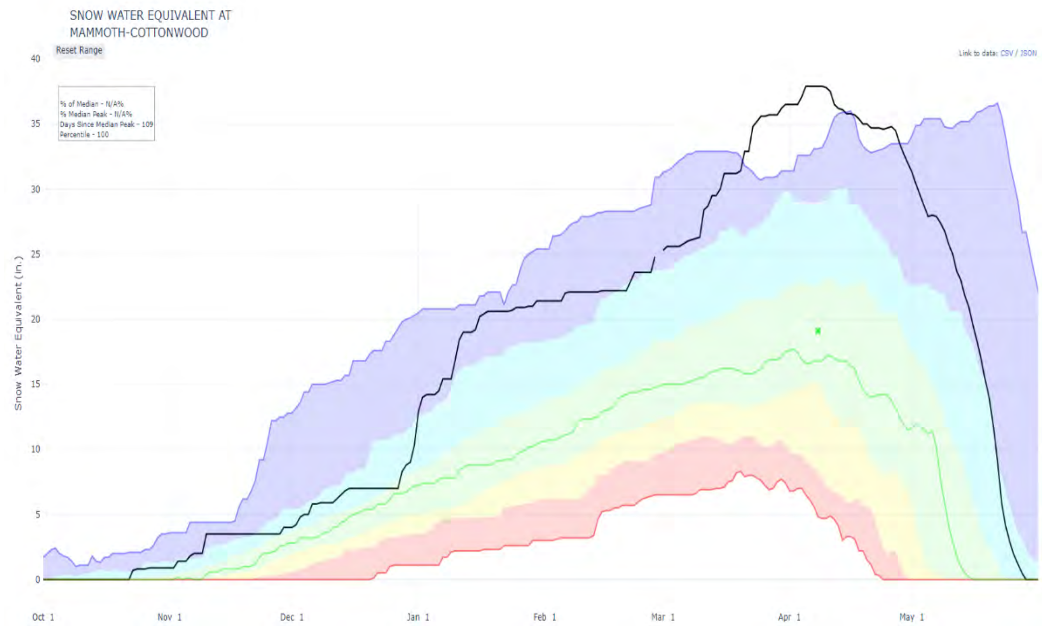


Figure 4.4. **NRCS SNOTEL snow water content plot for October 2022 through May 2023 for Mammoth-Cottonwood in Central Utah. Black line is the 2022-23 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.**

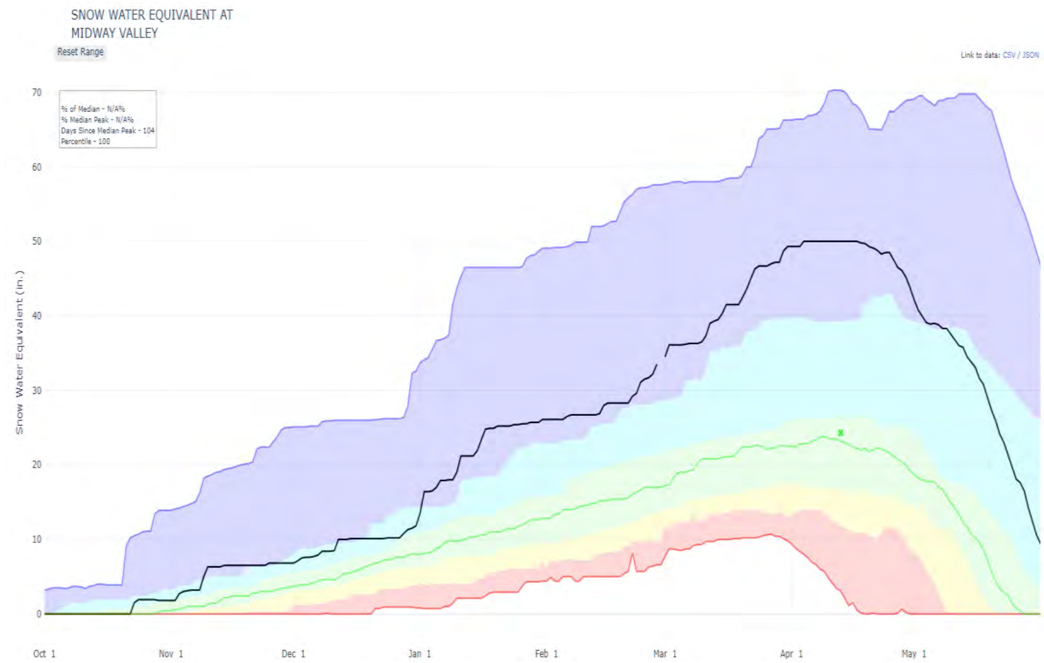


Figure 4.5. **NRCS SNOTEL snow water content plot for October 2022 through May 2023 for Midway Valley in southwestern Utah. Black line is the 2022-23 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.**

4.1 Operational Procedures

In operational practice, an approaching storm was monitored 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 Section 2.2 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 2022

The weather pattern for November was fairly active, particularly during the first half of the month when three storm systems affected the area. A fourth storm moved through near the end of November. All four of these storms saw seeding operations take place. Figure 4.6 shows precipitation for the month of November as a percentage of average precipitation by basin.

On November 2, an extensive cold frontal band associated with an upper level trough was located across central and southern Utah. 700 mb temperatures were falling below -5°C and were expected to dip to -8°C overnight. Most of the precipitation appeared to be coming from a higher cloud deck with southwest flow aloft, but a transition to a more convective mode as winds veered to northwesterly during the overnight hours. A number of sites in central and southern Utah were activated in the evening, with operations continuing into November 3 as light orographically-driven snow showers continued across much of the area. Seeding operations ended by late afternoon/early evening of the 3rd as the trough pushed east of the area. SWE totals ranged from approximately 0.3" up to around an inch.

Several mild days followed the first storm of the season, but on November 8, a large and deep semi-closed low was centered over the California coast. A baroclinic zone was set up across Utah, oriented SSW-NNE with 700 mb temperatures at or above 0°C ahead of it, and down to -4°C behind it across northwest Utah. Moderate to occasionally heavy precipitation and strong winds occurred in association with the boundary, but seeding did not occur during this period of the storm due to the warm temperatures aloft. By the morning of the 9th, temperatures aloft began to fall and a more convective nature to the convection developed so a number of sites in central and southern Utah were activated as precipitation developed in the southwest to westerly flow. Seeding continued through the morning and afternoon, with seeding ops ending by early evening as the trough axis passed through and precipitation tapered off. SWE totals were generally 0.5-1.5" but locally up to 3" was observed.

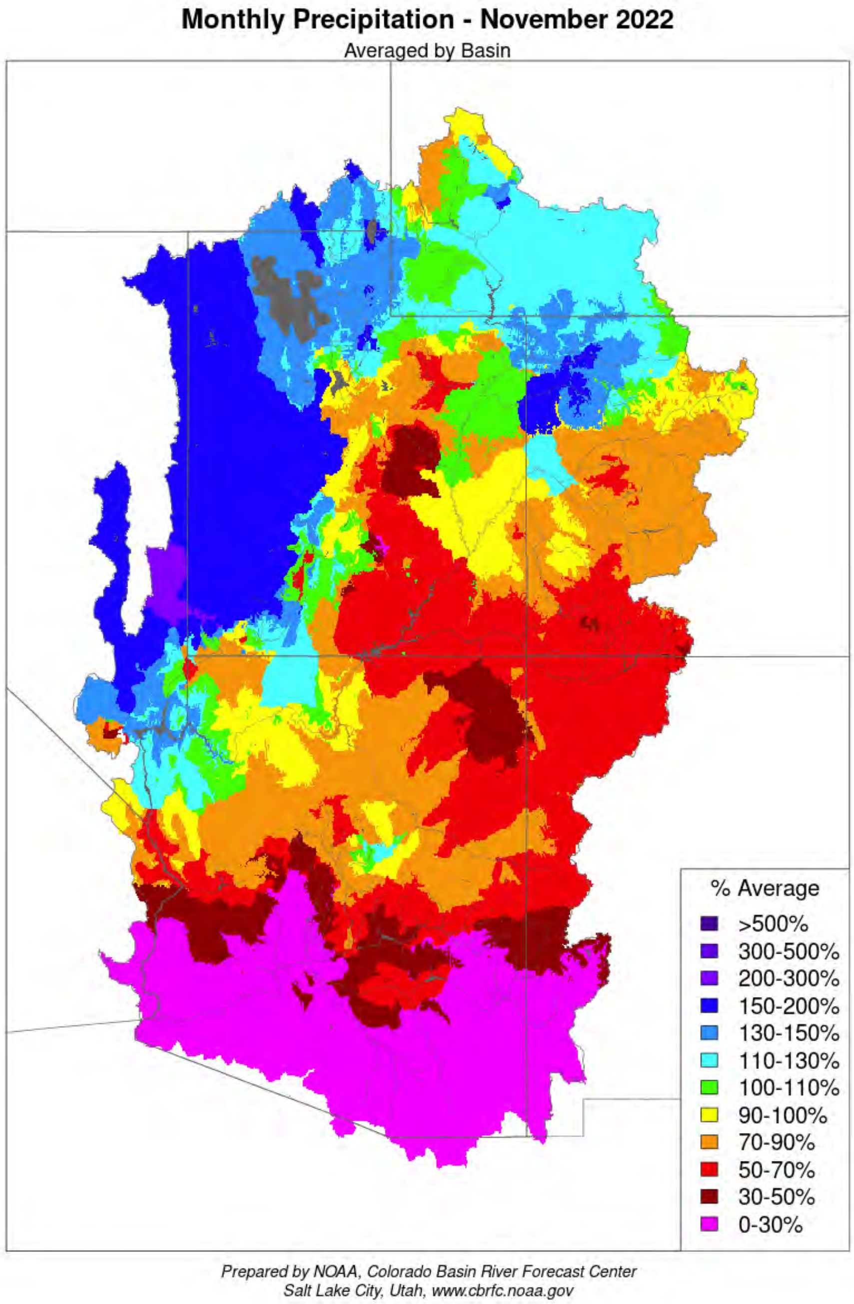


Figure 4.6. November 2022 precipitation, percent of normal.

A weak upper low pressure system approached southwest Utah during the morning hours of November 13. Light snow accompanied the system along with 700 mb temperatures of -10°C. While low level stability was an issue for some lower valleys, areas around Brian Head were above this and in a favorable location for seeding operations, so the site at Brian Head Summit was run for several hours during the afternoon. 0.1-0.2" of SWE was recorded. Beyond this day, an extended period of mainly high pressure with occasional very weak, insignificant disturbances affected the state through November 27.

On November 28, a large, deep trough of low pressure moved into Utah from the northwest. A cold front associated with the trough pushed into northern Utah during the morning hours, with a moist, unsettled northwest flow pattern translating in behind the front. Sites in Tooele County were activated toward the latter part of the afternoon hours, with sites further south across portions of central Utah activated in the evening. Convective snow showers continued into the overnight hours, ending by the morning of the 29th, at which time all sites were shut off. SWE totals of 0.1-0.5" were recorded.

December 2022

December saw an active weather pattern across Utah, with several disturbances affecting the state. Of these, four storm systems saw seeding operations take place. The early month events were not as favorable for seeding due either to strong winds or stability issues coming into play, but later in the month more significant and widespread events saw seeding operations ramped up. Figure 4.7 shows basin-averaged precipitation for the month.

A weakening trough of low pressure moved into the state on the morning of December 2 accompanied by strong winds mixing down to the surface across western Utah where High Wind Warnings were in place. A cold front accompanying the trough swept across the state bringing a period of heavy snow. Observations, both visually and through radar, indicated relatively low SWE, but decided to run a few sites across southwest Utah during the morning hours, ending by midday as the band of snow pushed off to the east. SWE accumulation was generally less than 0.5". From the 3rd through the 6th weak disturbances passed through Utah but low level stability and lack of moisture with these systems precluded seeding operations from occurring.

On December 7, an upper low moving into the Great Basin was accompanied by a zone of lift and moisture on its southeast flank, located across southern Utah; this is also where the left front quadrant of a jet streak was located. Snow levels were around 5500 feet with a slightly stable temperature profile in place. Early in the period no seeding took place at low levels (although the aerial program was active during this time). By early afternoon, a dry slot associated with the low moved into far southwest Utah, allowing for heating and the development of convective snow showers and thunderstorms. A couple of sites near the Pine Valley Mountains were activated during this time period, with bursts of heavy snow and graupel reported. Seeding ended by early evening. SWE content of 0.1-0.3" was recorded.

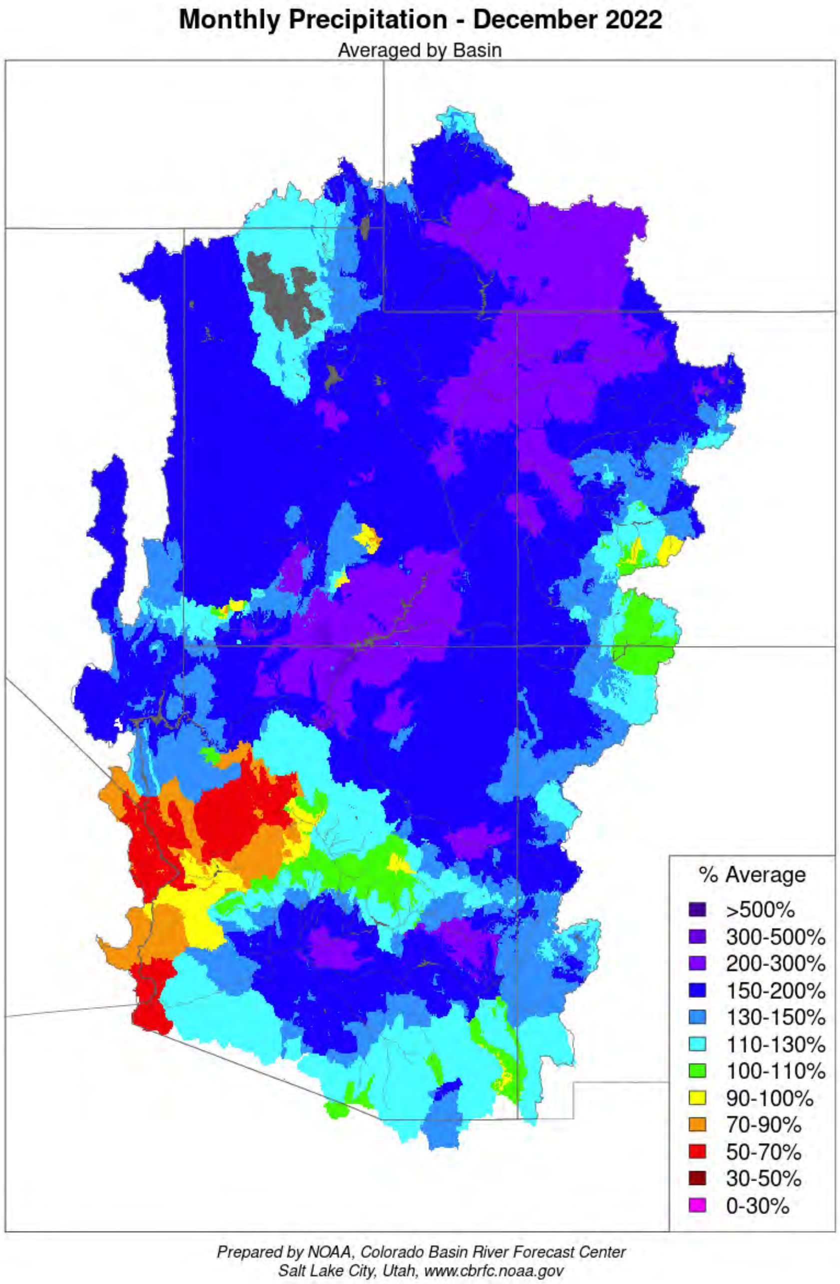


Figure 4.7. December 2022 precipitation, percent of normal.

The next significant storm system to affect Utah was on December 11; an upper level trough over the West Coast was slowly pushing eastward, with strong winds aloft spreading across Utah, where 500 mb winds were southwesterly at 60-70 kt, 700 mb winds were southwesterly 45-55 kt and surface southwesterly winds of 25-35 kt. Diffluent flow aloft was also spreading into the state, and this was promoting lift and precipitation development. PWAT values were around 0.6", indicative of good moisture availability. Across central and southern Utah, seeding had to wait until late afternoon/early evening when the strong winds had subsided to more ideal levels. By then, a number of sites in central and southern Utah were activated, with moist, unstable west to northwest flow promoting orographic snow showers that continued overnight. All sites were shut off on the morning of the 12th as precipitation had ended. Later in the day, however, snow showers developed along the Stansbury and Oquirrh mountains, and a couple sites were briefly activated for a couple of hours. SWE totals for this event ranged from around 0.3" up to 1.5" in some locations. From December 14-16, a couple of weak disturbances crossed the state but very cold temperatures aloft, stability issues and limited moisture precluded seeding. Fair weather was observed December 17-20. On December 21, a very cold trough of low pressure was digging into the central part of the country, bringing arctic air across the Rockies and central Plains. Utah was within the warm sector, and very strong winds were being reported in the mountains along with snow, however the winds were too strong for any seeding operations. Generally fair weather was observed across Utah from the 22nd through the 26th.

On December 27, a trough of low pressure was pushing onto the West Coast accompanied by rich moisture, some of which streamed into Utah with PWAT values of 0.6-0.8". 700 mb temperatures were initially above freezing and remained so until evening when they began to slowly fall. Precipitation was generally stratiform in nature and any stable layers that were in place early in the day had been eroded by evening, however with the warm temperatures aloft still in place, no seeding took place until after the cold front moved through by the morning of the 28th and a moist, unstable northwest flow pattern developed, allowing for orographically-driven snow showers and thunderstorms across the area. Localized seeding took place in Skull Valley (Tooele County) with more widespread seeding during the morning and afternoon across central and southern Utah. Precipitation tapered off by evening and seeding operations ceased. SWE totals of 0.3-1.3" were observed.

The month ended on a wet note, with a significant storm accompanied by an atmospheric river of moisture moving into Utah, but conditions were too warm and stable for seeding operations. This system continued to affect the area into January 1 with seeding operations occurring then.

January 2023

January was a busy month in terms of storm systems affecting Utah, with nine storm systems moving across over the course of the month, fairly evenly spread out. Of these, seven saw seeding operations take place, the most significant of which was on January 5-6. Figure 4.8 shows the basin-wide averaged precipitation for Utah for January 2023.

At the beginning of the month, a significant trough of low pressure accompanied by rich moisture and warm temperatures both at the surface and aloft were moving toward Utah. Low levels were stable so initially ground seeding was not an option. Areas of heavy rain (with high elevation snow) occurred, especially across southwest Utah where Flash Flood Warnings were issued from mid-morning into the afternoon hours. Late in the afternoon, cooler air aloft began to filter into the southwest part of the state, and although most low level sites were still dealing with stability issues, decided to activate the Brian Head Summit site as it was above the inversion. Seeding from Brian Head continued through the night and into the following morning before being shut off. SWE totals for the storm period from Dec 30-Jan 2 were in the 0.5-3.0” range.

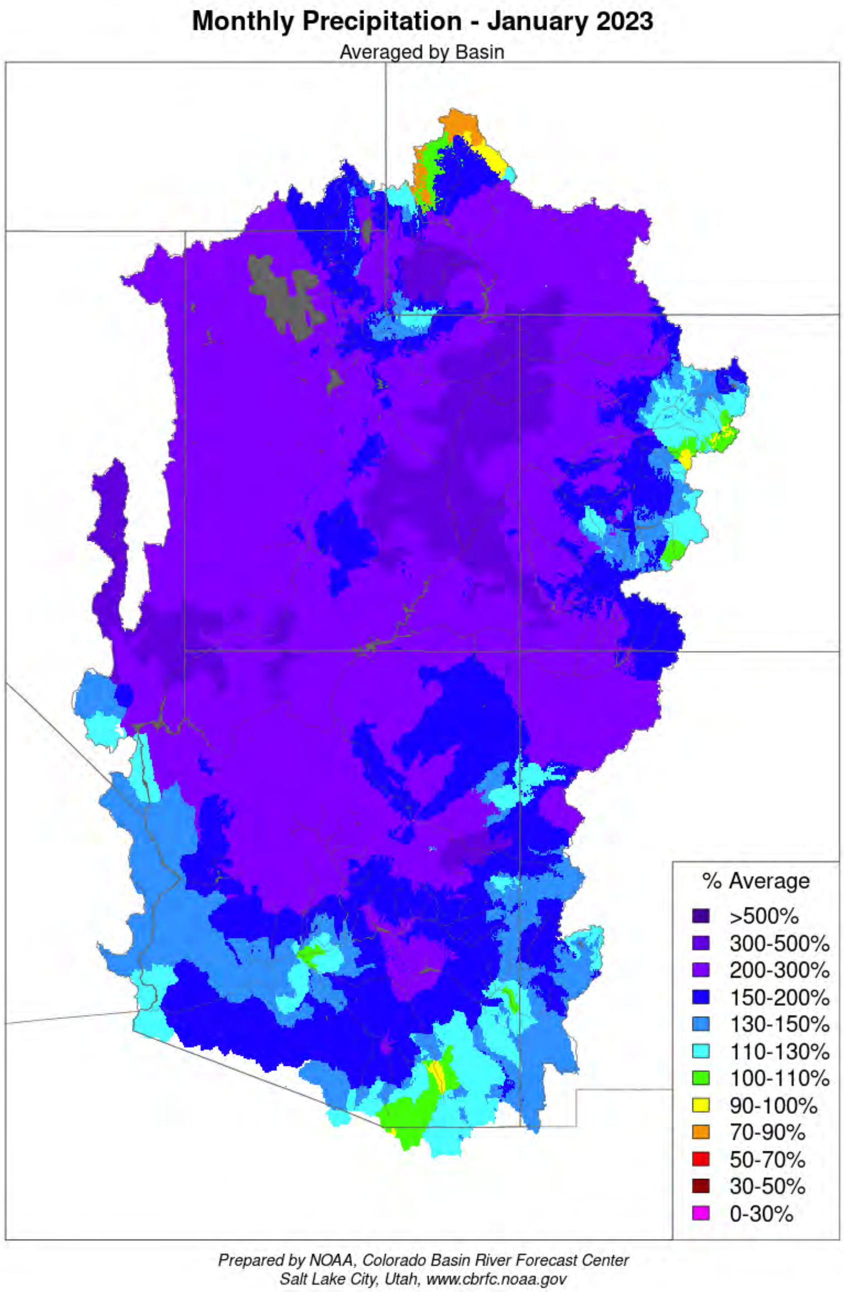


Figure 4.8. January 2023 precipitation, percent of normal.

A weak disturbance passed across southern Utah on the 3rd accompanied by a few sparse areas of light rain and snow, with snow levels down to 3000 feet in Washington County. Precipitation didn't last long. High pressure moved into the area on the 4th with below average temperatures. A mid-level warm front crossed the state during the evening ahead of the next storm system, which began to affect the state on the 5th. A trough of low pressure over California was moving east toward the area, with a plume of moisture accompanying the trough. Broad upper level diffluence on the forward side of the trough spread into southern and western Utah during the afternoon where precipitation was developing and expanding across the area. With the statewide impact of this storm, many sites were activated across central and southern Utah during the afternoon and evening, as well as in Tooele County. Precipitation continued overnight into the morning of January 6, tapering off across southern Utah where sites were shut off. Further north across central and northern Utah, convective development occurred from late morning into the afternoon so those sites continued to run until late afternoon before being shut off. SWE totals for this storm event ranged from around 0.5” to 2.0”. High pressure moved in behind the departing trough, with fair weather for the 7th and 8th, although some light snow showers fell across northern Utah.

A trough of low pressure moved across Utah on January 9 accompanied by rain, high elevation snow, strong winds and warm mid-level temperatures associated with a weakening atmospheric river setup. No seeding took place in central or southern Utah with the disturbance passing to the east early on the 10th. A second disturbance, however, quickly moved in behind the first later in the day, accompanied by a cold front that had rain, snow and thunderstorms along it in addition to strong winds both at the surface and aloft. The expectation was for moist, unstable west to northwest flow to develop behind the cold front leading to orographic convective snow showers, and as such, a number of sites in Tooele County and central Utah were activated during the evening, with fewer sites activated across southern Utah. Snow showers continued through the night, ending early on the 11th, at which time sites were shut off as the disturbance exited the state. SWE totals from the storm ranged from 0.5” to as much as 4.0” in some locations.

The next disturbance to affect the state arrived on the 14th. A trough over the West Coast was moving east toward the Intermountain West. A strong upper level jet (150+ kt) combined with upper level diffluent flow was approaching southwest Utah by mid-afternoon. Dry low levels initially meant lots of virga around west and southwest Utah, but as the low levels moistened up, precipitation eventually began to reach the ground. With precipitation expected to continue into the overnight period, sites in south and southwest Utah were activated during the evening and ran overnight. On the 15th, precipitation continued across central and southern Utah, and a few more sites were activated around the Skyline area as convective snow showers were developing and pushing east into the mountains. Seeding continued through the afternoon of the 15th, and all sites were shut off by 2000 MST that evening. SWE totals for the event ranged from 0.5” to 2.5”.

A longwave trough of low pressure was situated over the West Coast on the 16th, and an embedded disturbance ejected from the trough and moved into southwest and west-central Utah during the afternoon, with scattered rain/snow showers and thunderstorms. Sites in and around the Pine Valley Mountains as well as along I-15 in Millard County were activated to seed the convective cells as they moved across the area, with all activity and seeding ending during the evening. The longwave trough began to move into Utah on the 17th with embedded shortwave disturbances continuing to flow through it. One such disturbance was expected to evolve into a closed low near the Four Corners region. As the trough axis passed through west and southwest Utah during the day, moist and unstable northwest flow developed in its wake, with scattered convection developing along I-15. Sites across southwest Utah were activated during the afternoon to treat these cells, with seeding operations finishing up by early evening as activity came to an end. SWE totals for the two-day period were generally in the 0.5-1.0” range.

An active weather pattern continued, and after a passing ridge of high pressure on the 18th, another trough of low pressure pushed into Nevada and dug southeast toward Las Vegas, where it was expected to transition into a closed low. Early precipitation radar echoes across southwest Utah were indicative of virga given the dry low levels but soon after precipitation began reaching the ground, with snow being reported in St. George. 700 mb temperatures were -8°C to -12°C. Given the limited amount of moisture and cold temperatures, only a few sites around Brian Head and Pine Valley were activated, and these sites ran through the night, ending on the 20th as precipitation tapered off. SWE totals of 0.25-0.50” were reported.

For the remainder of January, very weak, disorganized disturbances passed across Utah with very light precipitation, cold temperatures and little moisture. No seeding took place during this time period, as conditions were not suitable for seeding operations.

February 2023

February 2023 saw the trend of a very active weather pattern continue. Eight storm events affected the state during this time period, seven of which saw seeding operations take place. Figure 4.9 shows the precipitation as a percent of average for the different basins in the CBRFC forecast area.

The first several days of the month were cold and dry with strong valley inversions in place. On February 5, a trough of low pressure was located west of the state. Upper level diffluent flow on the forward side of the trough began to spread across western Utah, aided by a 125-150 knot jet streak. Moisture availability wasn’t great, with PWAT values of 0.25-0.40” tied mainly to the cold front along the Utah/Nevada state line around midday. Many seeding sites in central Utah and some sites in southern Utah were activated to treat the clouds associated with the front during the afternoon, with seeding ending in the evening as precipitation tapered off. With the trough still over the area on the 6th but the trough axis now east of the target area, northerly to northwesterly flow was promoting orographic snow showers across northern Utah and southwest Utah. Sites in the southwest were activated around midday and continued until early evening, when activity tapered off. SWE totals for the two days were in the 0.1-0.5” range. Aside from a cold front affecting northern Utah on the 8th, the week from the 7th through 13th was generally quiet with high pressure and strong inversions in place.

A very cold trough of low pressure dropped into the Great Basin from the Pacific Northwest on the 14th. A cold front just ahead of the trough pushed into central and southwest Utah in the morning accompanied by light snow falling from a higher cloud deck. As the base of the trough approached southwest Utah, precipitation expanded and increased in intensity, with isolated thunderstorms developing as well. Several sites in southwest Utah were activated around midday and continued through the afternoon as activity continued to stream across the area. Precipitation tapered off by evening as much colder air aloft moved in (700 mb Ts -15°C). SWE totals up to 1.25” were recorded. After this storm system, a period of quieter weather was observed across Utah from the 15th through the 20th.

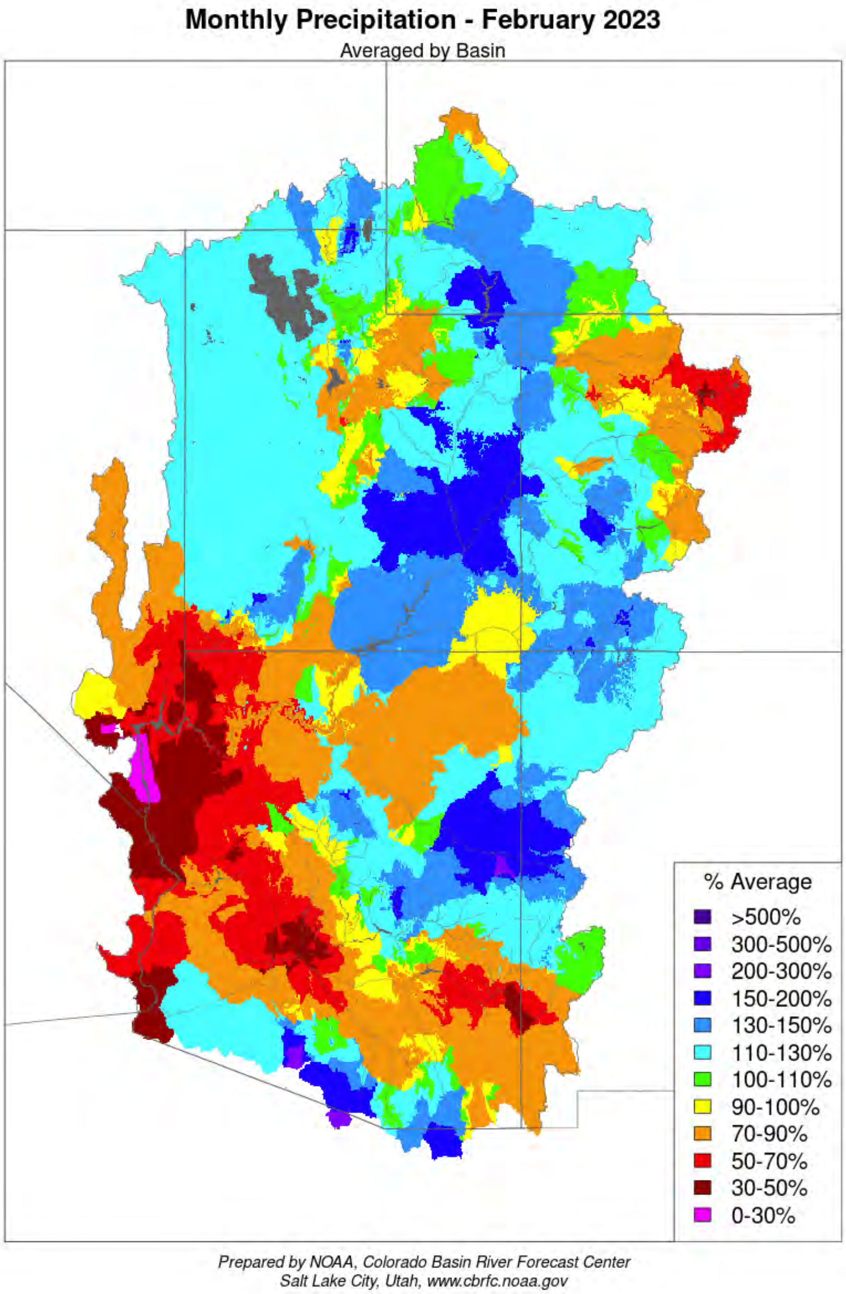


Figure 4.9. February 2023 precipitation, percent of normal.

A cold trough of low pressure was digging south across the western United States on the 21st. A cold front pushed into northern Utah during the afternoon and, by early evening extended from near Evanston, WY to southwest Tooele County. High Wind Warnings and Wind Advisories were in place south and east of the front, across central and southern Utah which would preclude any seeding operations from taking place as sustained winds of 25-40 mph were realized with gusts reaching 60-70 mph. 700 mb temperatures near the front were around -5°C across northern Utah but were expected to drop down to -15°C by the morning of the 22nd. With the expansive precipitation across Tooele County, most sites there were activated during the evening and continued to run into the afternoon of the 22nd, even as temperatures aloft dipped to -15°C. With little in the way of supercooled water being observed, seeding operations ended in Tooele County. SWE totals were in the 1.0-3.0" range across the Tooele County mountains.

On February 23, a deep trough was covering most of the western U.S., centered over the Oregon coast and inducing southerly to southwesterly flow across Utah. 700 mb temperatures were rather cold, -12°C to -14°C. Although initially moisture wasn't great, the continued south to southwest flow began to introduce more moisture into southwest Utah, where scattered convection began to develop by mid-afternoon. Model guidance was indicating this pattern to increase across southwest Utah and continue overnight; as a result, several sites in southwest Utah were activated during the afternoon hours, and continued to run through the night, with seeding operations ceasing early in the morning of the 24th. Further north, convection was glaciating too quickly and, as such, no seeding operations took place. SWE totals were on the low side, ranging from 0.1-0.5".

On February 25 and early February 26, a cold core low moved across southern California and southern Nevada. Warm temperatures aloft prevented ground seeding from taking place as well as strong winds. Precipitation did fall across southwest Utah, mainly Washington County.

On February 27, a longwave trough was digging southeast through the Pacific Northwest into the Great Basin, with embedded shortwave disturbances moving through the trough; the first of these disturbances moved across northern Utah during the morning and afternoon hours bringing snow showers with a second disturbance in Nevada moving into Utah during the overnight hours into the 28th. Ahead of this second disturbance, precipitation increased quickly across southwest Utah underneath a 250mb jet streak of 100-130 kt and where 700 mb temperatures were around -9°C/-10°C. Strong winds were anticipated to develop overnight across mainly the western half of the state as well as over parts of northern Utah with gusts to 55 mph, and this resulted in limited seeding potential. Still, sites around southwest Utah, particularly around Brian Head and the Pine Valley mountains were activated and ran through the evening of the 27th into the morning hours of the 28th before being shut off as precipitation had ended. SWE totals for this event were in the 0.5-1.0" range. Another round of precipitation developed during the late afternoon and evening hours of the 28th which would continue into March 1, and this will be discussed in the March section.

March 2023

March was an active month of weather, continuing the trend observed for much of the winter season. Nine storms affected the target area over the course of the month, eight of which saw seeding operations take place. Areas around the Virgin River headwaters (Pine Valley Mountains, Cedar Breaks area near Brian Head) were placed under suspension at mid-month due to the excessive snowpack in place, with fears of significant flooding in the spring. Figure 4.10 shows the basin-averaged precipitation across the CBRFC area.

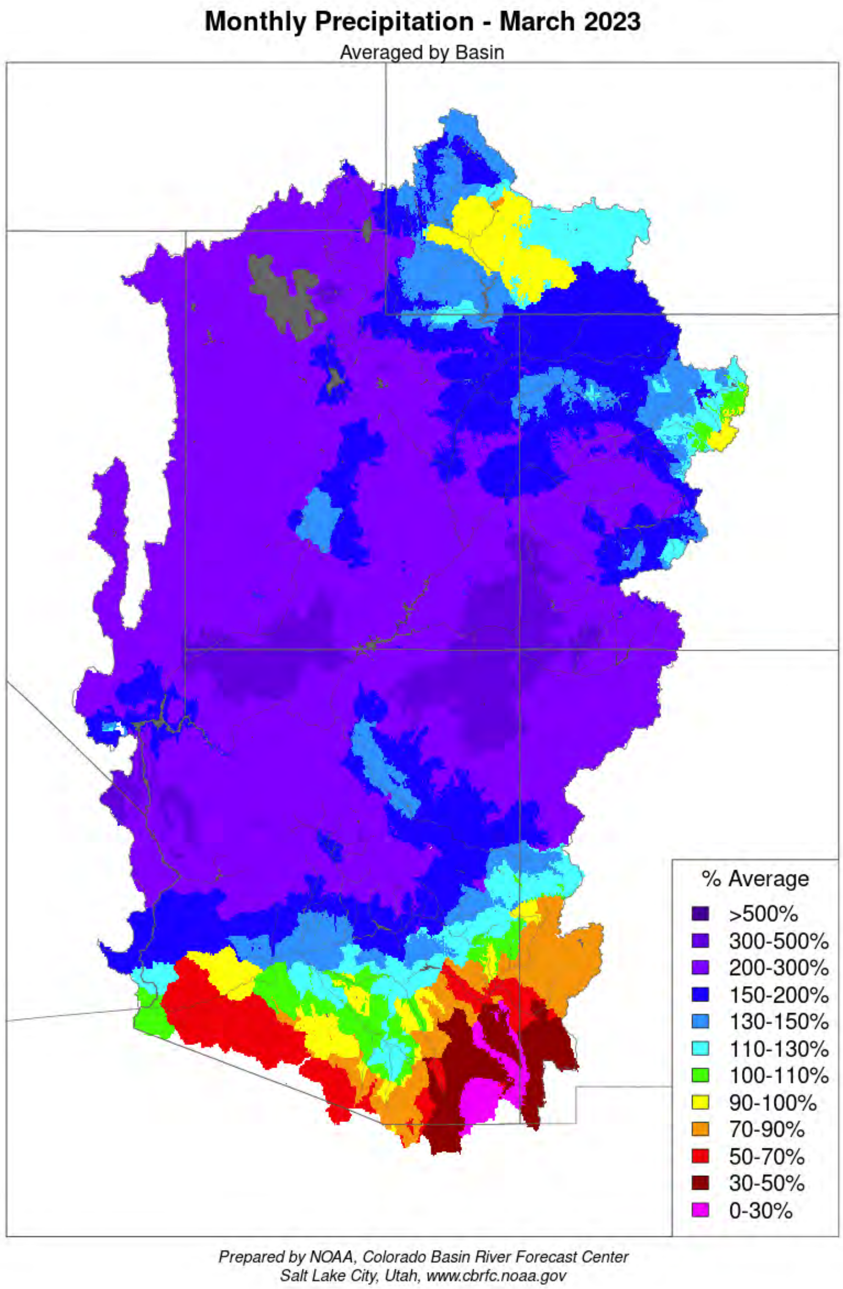


Figure 4.10. **March 2023 precipitation, percent of normal.**

A cold trough of low pressure was digging into the western U.S. on February 28, and by evening precipitation began to blossom across southwest Utah as southerly upslope flow increased while diffluent flow aloft spread over the area. 700 mb temperatures were around -10°C over southern Utah and -13°C across the north. Sites in southwest Utah were activated in the evening of the 28th and continued to run into the morning of March 1 as precipitation continued across the area. Another incoming wave with associated precipitation moved into southwest Utah late morning of the 1st and continued into the afternoon hours before tapering off late in the afternoon; at that point sites were deactivated. SWE totals for the storm event ranged from approximately 0.1-0.5". Tranquil weather was observed across Utah on March 2-3.

A longwave trough was located across the Pacific Northwest/Great Basin/northern Rockies on March 5 with west-southwest flow across Utah. A disturbance was moving east across Nevada during the day with snow showers and isolated thunderstorms on the leading edge pushing into western Utah from Juab County northward during the afternoon and early evening. A surface boundary, left over in central Utah from an earlier disturbance was beginning to move back to the north and was expected to stall somewhere across Tooele County into the Wasatch Range overnight. Moisture availability was good and 700 mb temperatures were around -9°C. Snow developed across Tooele County early in the evening and continued overnight. Most Tooele County sites were activated and ran through the night, ending early on the morning of the 6th as precipitation tapered off. SWE totals up to 0.5" were recorded. Scattered snow showers developed across northern Utah on the 7th while the rest of the state was fair.

A disturbance emanating from a trough over the Pacific Northwest/northern California moved into Utah during the afternoon hours of March 8. Unstable conditions arrived with the disturbance and associated cold front. Two waves of precipitation were observed, the first during the afternoon hours ahead of and along the cold front with isolated thunderstorms as well, and a second wave of precipitation in the evening behind the cold front. Sites across Tooele County and central Utah were activated for both waves of precipitation, with seeding ending by 2200 MST. A ridge of high pressure traversed the state on the 9th with tranquil weather conditions.

A storm system with rich moisture and warm temperatures moved into Utah on March 10. 700 mb temperatures rose to near or just above freezing. Rain and thunderstorms, with higher elevation snow, fell across the state. Conditions were unfavorable for seeding. Precipitation continued on March 11 with a stalled frontal boundary across central Utah. Mid-level temperatures remained warm, and this precluded seeding operations. Some upslope rain/snow showers occurred across the northern Utah mountains on March 12, but the best conditions were east of the target area. Mild conditions on March 13-14 precluded seeding operations. On March 15, although marginal conditions for ground seeding were in place for some areas of southern Utah, Flash Flood Warnings prevented seeding operations from taking place. Fair and tranquil weather was observed from March 16-18. **Beginning on March 16, areas around the Virgin River headwaters, specifically the Pine Valley Mountains and the Cedar Breaks area were placed on suspension due to excessively high snowpack in these areas suggesting a risk for flooding along the Virgin River in the spring. No seeding from this point forward would impact this area.**

Quasi-zonal flow was in place from the eastern Pacific across California and into the Great Basin on March 19 with embedded shortwave disturbances moving through the flow aloft. One such shortwave was moving into southwest Utah during the afternoon hours accompanied by southerly flow and precipitation. 700 mb temperatures were around -5°C and snow levels were around 6500 feet. Dry air at low levels resulted in early precipitation falling as virga, but by evening precipitation was reaching the ground. Sites in central and southwest Utah were activated during the evening and ran through the overnight period as precipitation and ideal seeding conditions continued. Operations ceased on the morning of the 20th as precipitation ended and the disturbance passed east of the area, but a second disturbance approached from the west by midday with additional snow showers and thunderstorms redeveloping across southwest Utah during the afternoon hours; southwest sites were re-activated and ran from midday until late afternoon/early evening as convection waned. SWE for the two-day period ranged from 0.5-1.5”.

On March 21, a large, cold upper low off the central California coast was slowly pushing east/southeast. Diffluent flow ahead of the low spread into southern Utah in the morning which promoted the development of widespread light rain/snow across the area. Area observations did indicate some minor stability issues in most valleys, but a combination of warming and increased winds would erode the stable layers during the day. Precipitation continued across southwest Utah into the afternoon hours with a break mid to late afternoon as a dry slot moved into the area. Additional precipitation developed within this dry slot and several sites were activated across southwest Utah. Winds increased during the evening across many areas, including some sites where active seeding was going on and this may have impacted the seeding plumes, making some of them exceptionally long and diffuse. Seeding continued across the far southwest through the night, with operations ceasing on the morning of the 22nd as precipitation tapered off. SWE totals for the event were generally 0.5-1.5”, with up to 3.0” in some areas. Additional snow showers developed over Utah later in the day and again on the 23rd, but low moisture content and quick glaciation precluded seeding operations from occurring in the target area.

A very cold shortwave disturbance trough moved across northern and central Utah on March 24 accompanied by a cold front that crossed the state. 700 mb temperatures around -9°C in the morning fell to -15°C/-17°C later in the afternoon behind the front. Moisture availability was marginal with PWAT values of around 0.3”, but convective development, including snow squalls, was expected to occur across central Utah, where the best opportunity for seeding appeared to be, and seeding took place from 1015/1030 MDT until 1700 MDT. SWE totals for this event were generally around 0.2-0.5”.

The last storm event of the month began on March 29. A cold upper level trough was located along the California coast pushing southward, with upper level diffluent flow across Utah and a 120 kt jet streak oriented SW-NE across the state. Strong winds aloft were mixing down to the surface with gusts exceeding 50 mph across western Utah. A band of moisture along a cold front was pushing east across the state. No seeding took place on the 29th due to the strong winds in place. Behind the cold front, moist unstable flow set up, aided by cooling temperatures aloft (700 mb temps falling to -10/-11°C) and scattered rain/snow showers and thunderstorms developed from late morning through the afternoon across central and southern Utah. Seeding operations were initiated in these areas beginning late morning of the 30th, continuing until early evening when precipitation tapered off. SWE totals of 0.5-1.0” were observed.

April 2023

After a very busy winter season, April 2023 turned out to be much quieter weather-wise, with only one storm event occurring during the first week of the month. Precipitation totals were below average, as indicated in Figure 4.11.

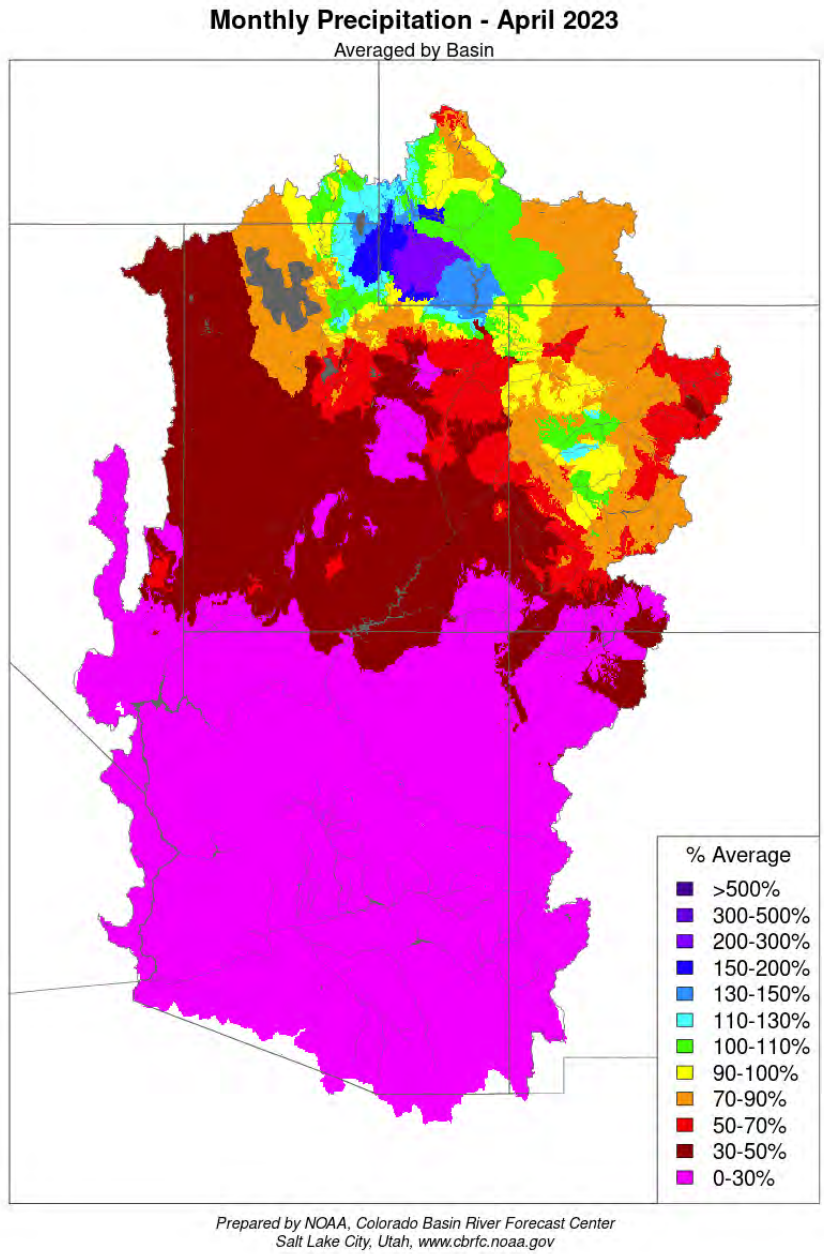


Figure 4.11. April 2023 precipitation, percent of normal.

On April 3, a trough of low pressure was located over the Pacific Northwest/Great Basin with axis stretching from Alberta to northern California, moving east. A strong baroclinic zone was oriented from southwest Wyoming to southern Nevada pushing slowly southeast. Strong southwesterly winds ahead of the front were in place, with gusts to 60 mph. Precipitation was occurring along and behind the frontal boundary, with much colder air and convective cells behind the front, where 700 mb temperatures were at -15°C/-17°C and 500 mb temperatures were as low as -36°C. Seeding began around midday across central Utah, with additional sites in southern Utah activated late in the afternoon. Seeding continued overnight as snow showers remained active but ended on the morning of the 4th as activity waned and temperatures continued to cool to levels not favorable for seeding. SWE totals were generally in the 1.0-2.0" range. This turned out to be the final seeding event for the 2022-23 season for the Central and Southern Utah program.

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 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 database 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.

5.3.1 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.

5.3.2 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.

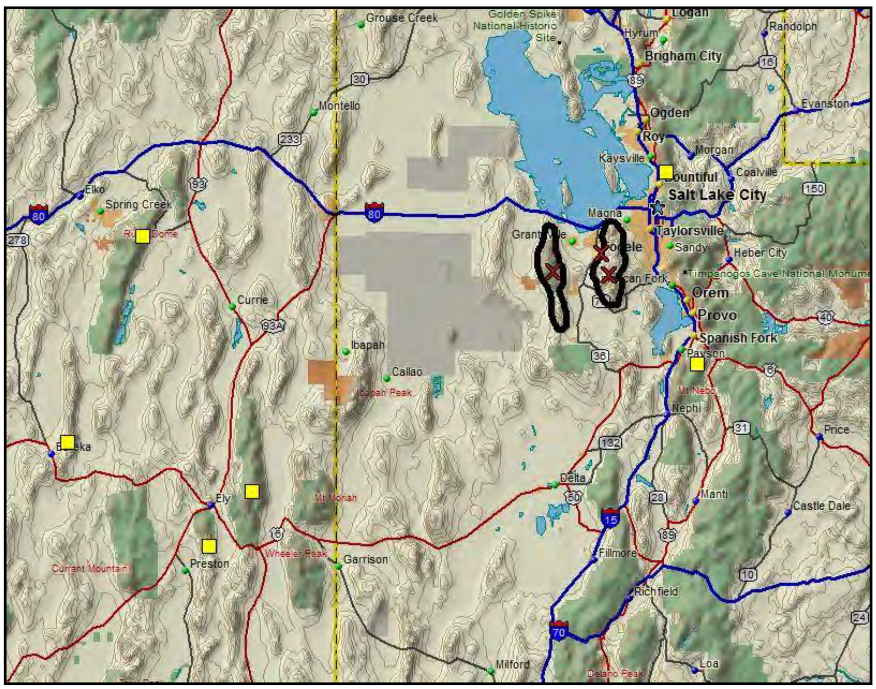


Figure 5.1. **Precipitation sites for Eastern Tooele target/control evaluation; control sites are depicted as squares and target sites with an X.**

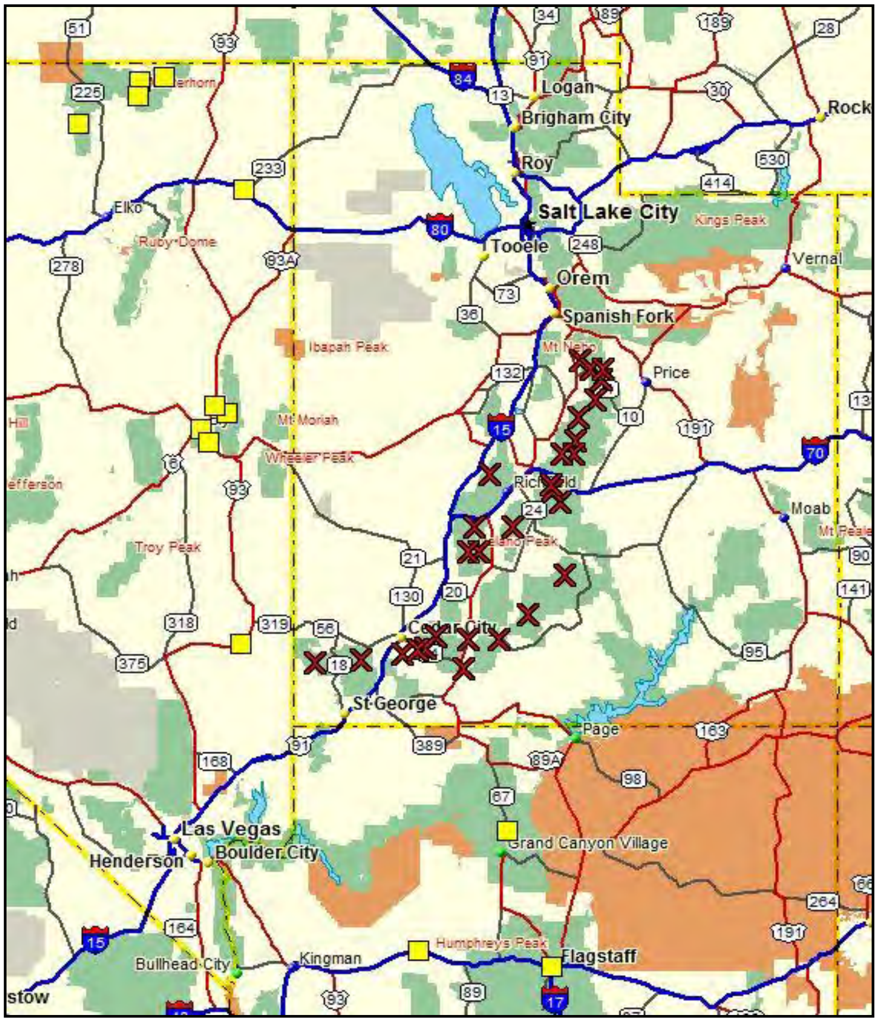


Figure 5.2. **Precipitation target (X) and control (square) sites, primary target area.**

5.3.3 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 1996-2023 (39 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 46 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.

5.3.4 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 2022-2023 December-March season and for all seeded seasons

Target Group	Seeded Period	Ratio	Increase (inches)
E. Tooele Co.	39 Seeded Water Years	1.13	1.5
	2023 Water Year	1.59	9.1
Primary Target	46 Seeded Water Years	1.11	1.2
	2023 Water Year	0.86	-2.7

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

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
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
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
2022	8.3	8.4	0.99	-0.1
2023	24.3	15.3	1.59	9.1
Seeded Mean	**12.6**	**11.1**	**1.13**	**1.5**

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

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
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
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

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
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
2022	11.0	7.6	1.44	3.4
2023	16.3	19.0	0.86	-2.7
Seeded Mean	**12.1**	**10.9**	**1.11**	**1.2**

5.3.4.1 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 39 seeded seasons and 28 non-seeded seasons in the regression period. For the single season (2022-2023) evaluation, the regression equation resulted in an observed/predicted ratio of 1.59 as shown in Table 5-3a. This is a 59% 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 39 seeded seasons the observed precipitation within the target has averaged 13 percent greater than might have been expected from calculations based on the control precipitation averages. That increase is equal to an average additional 1.5 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.

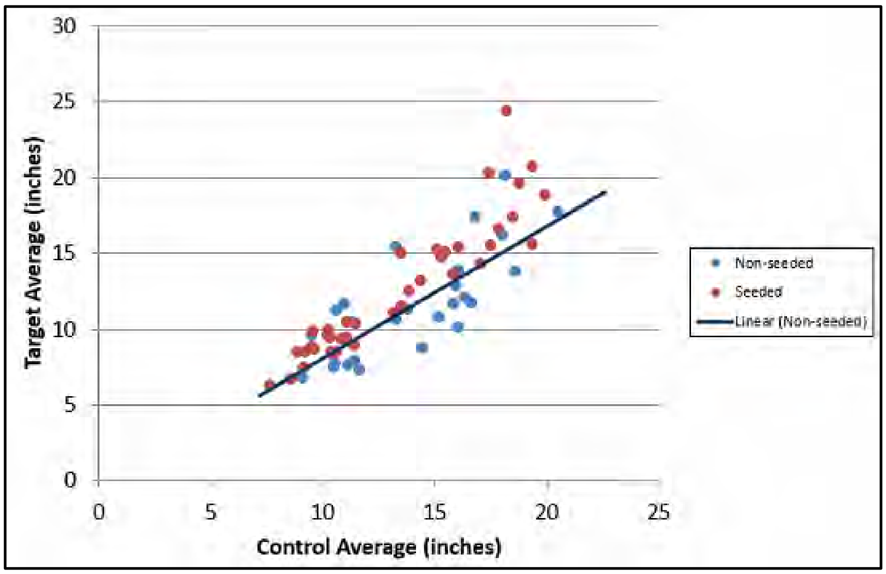


Figure 5.3. **Scatterplot of historical non-seeded (blue) vs seeded (red) data points for the eastern Tooele County precipitation evaluation. The diagonal line represents the linear regression equation for the non-seeded period.**

5.3.4.2 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 46 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 2023 water year, the target/control precipitation evaluation results (from Table 5-2) yielded an observed/predicted ratio of 0.86, indicating that 14% less 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 46 seeded years included in the long-term seeded record, 11 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 1.2 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 15^{th}-30^{th} 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.

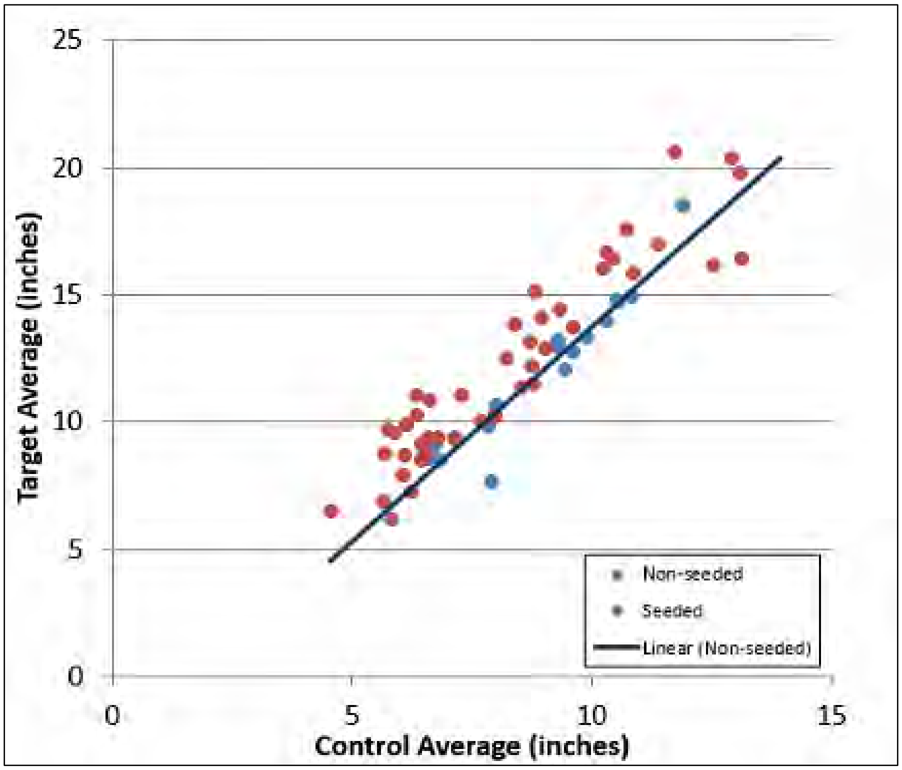


Figure 5.4. **Scatterplot of historical non-seeded (blue) vs seeded (red) data points for the primary target precipitation evaluation. The diagonal line represents the linear regression equation for the non-seeded period.**

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.

5.4.1 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.

5.4.2 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.

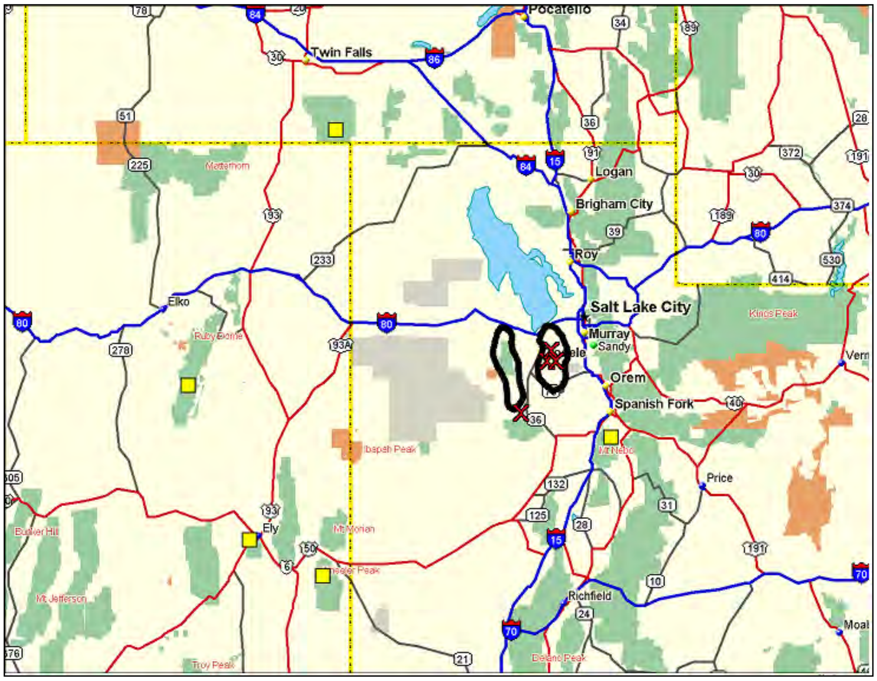


Figure 5.5. **SWE sites for Eastern Tooele target/control evaluation (squares are control sites, X's are target sites).**

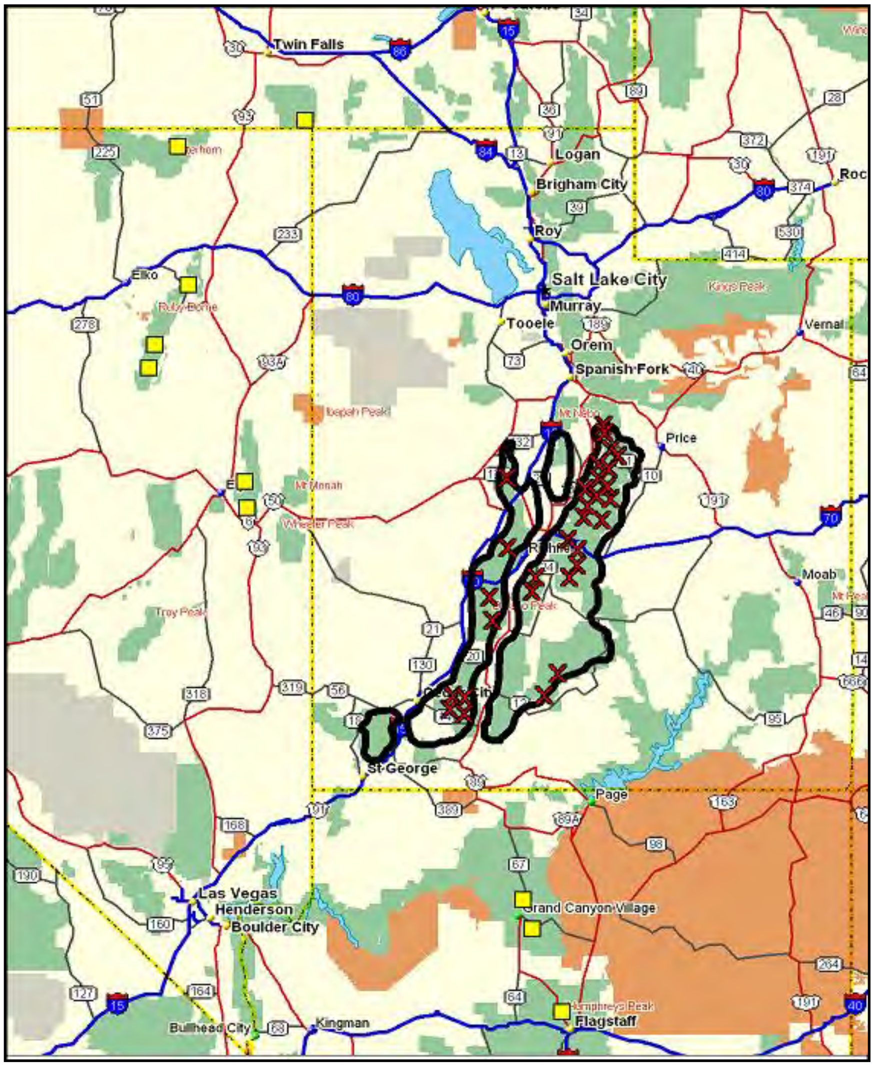


Figure 5.6. SWE sites for Primary Target evaluation (squares are control sites, X's are target sites)

5.4.3 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

5.4.4 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, 2017 and 2022 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 2022-2023 season, and for all seeded seasons

Target Group	Seeded Period	Ratio Y_o/Y_c	Increase Y_o-Y_c
Eastern Tooele (ETT)	35 water years*	1.10	1.3
	2023 water year	1.09	2.4
Primary Target (PT)	42 water years*	1.04	0.5
	2023 water year	0.78	-5.8

*** 2007, 2012, 2015, 2017 and 2022 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.

5.4.4.1 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, 2017 and 2022 (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 1.13 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 1.09 which suggests a 9% 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

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
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
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
2022*	5.4	8.2	0.66	-2.8
2023	29.7	27.3	1.09	2.4
Seeded Mean	**14.7**	**13.4**	**1.10**	**1.3**

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

5.4.4.2 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 1.11 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 0.5 inches per year in the snow water analysis and 1.2 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
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

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
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
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

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2022	10.6	8.4	1.26	2.2
2023	20.5	26.3	0.78	-5.8
Seeded Mean	**14.6**	**14.1**	**1.04**	**0.5**

*** 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.

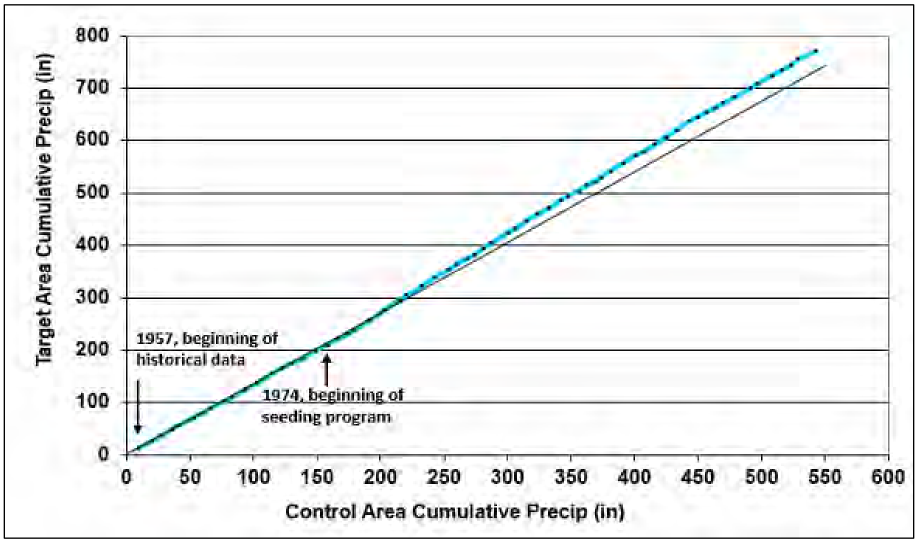


Figure 5.7. **Double-Mass plot for Primary Target; all seasons shown after 1974 in this plot were seeded, and all the seasons plotted previous to this were not seeded.**

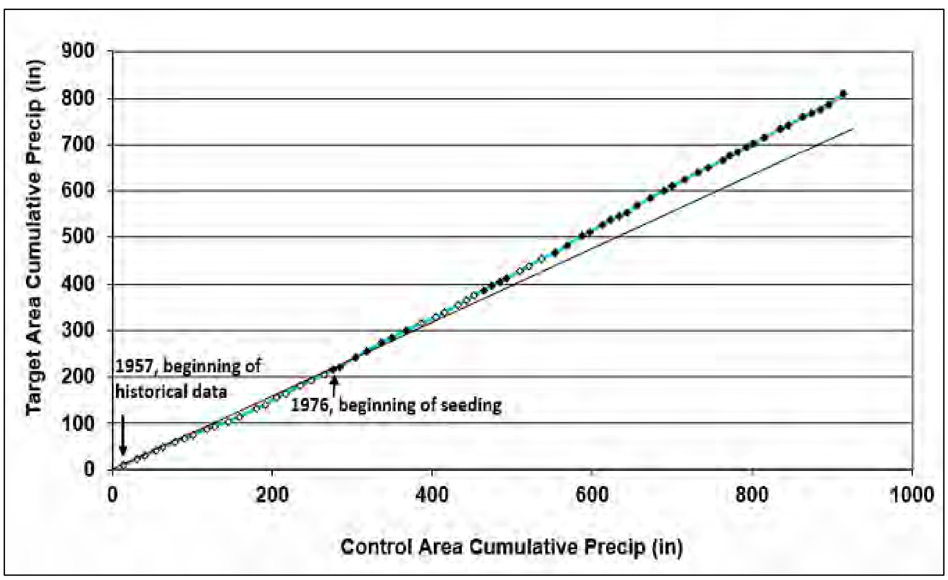


Figure 5.8. **Double-Mass plot for Eastern Tooele County Target; smaller data points denote non-seeded seasons, and larger, darker points are the seeded seasons.**

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 10-13% increase in precipitation/snow water for the ETT, with a range of 4-11% 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

	2023 Water Year	**Long-term Average**
ETT Precipitation Linear	1.59	1.13
ETT SWE Linear	1.09	1.10
PT Precipitation Linear	0.86	1.11
PT SWE Linear	0.78	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 are:

- Excess snowpack accumulation
- Rain-induced winter flooding
- Severe weather

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.

Project & Basin	Critical Streamflow Volume (Acft) & USGS Streamgage	SNOTEL Station	SWE Value Corresponding to the Critical Flow								Ranking of SNOTEL Stations
			Jan 1 (in.)	Jan 1 (%)	Feb 1 (in.)	Feb 1 (in %)	March 1 (in.)	March 1 (in %)	April 1 (in.)	April 1 (in %)	
1. Northern Utah	185,208	Franklin Basin, Idaho	19.50	190.84	27.14	165.31	34.35	154.71	41.56	153.60	1
Logan at Logan	USGS 10109000	Tony Grove	28.73	205.94	39.44	175.56	48.06	160.38	56.34	156.56	2
		Bug Lake	17.08	218.82	21.91	180.34	26.72	165.25	31.65	162.70	3
		Average	**21.80**	**205.20**	**29.50**	**173.70**	**36.40**	**160.10**	**43.20**	**157.60**	
Weber near Oakley	176,179	Chalk Creek #1	10.09	173.13	14.73	153.66	28.77	149.85	34.15	143.41	1
	USGS 10128500	Trial Lake	20.15	207.44	26.33	180.55	33.55	173.27	38.54	162.28	2
		Smith Morehouse	10.06	186.34	13.69	137.60	17.36	146.32	21.17	160.26	3
		Hayden Fork	12.19	194.16	16.69	172.11	20.71	158.56	21.79	164.64	4
		Average	**13.10**	**190.30**	**17.90**	**166.00**	**25.10**	**157.10**	**28.90**	**157.70**	
Dunn Creek near the Park Valley	5,733	George Creek	17.84	187.75	18.32	143.81	28.93	163.43	34.61	153.77	1
	USGS 10172952	Howell Canyon, Idaho	28.71	279.96	38	223.24	44.59	205.98	50.46	191.65	2
		Average	**23.30**	**233.90**	**28.20**	**183.60**	**36.80**	**184.70**	**42.60**	**172.70**	
2. Western & High Uintah	166,861	Lily Lake	11.38	202.70	16.40	194.06	17.69	147.37	28.93	139.19	1
Bear River near Utah - Wyoming state line	USGS 10011500	Trial Lake	20.07	206.54	26.56	182.26	33.68	173.94	38.49	162.05	2
		Hayden Fork	12.41	197.65	17.06	175.83	21.03	160.98	20.90	146.02	3
		Average	**14.60**	**202.30**	**20.00**	**184.10**	**24.10**	**160.80**	**29.40**	**149.10**	
Duchesne near Tabiona	140,976	Strawberry Divide	6.92	239.23	10.87	199.25	26.77	178.78	29.75	179.05	1
	USGS 09277500	Daniels-strawberry	16.07	248.12	21.59	202.44	27.82	190.54	29.89	192.75	2
		Smith Morehouse	10.61	196.64	14.95	172.41	18.82	158.83	22.22	168.26	3
		Rock Creek	8.76	230.02	12.31	219.65	15.88	205.68	16.41	209.06	4
		Average	**10.60**	**228.50**	**14.90**	**198.50**	**22.30**	**183.50**	**24.60**	**187.30**	
Provo near woodland	183,845	Trial Lake	22.98	236.53	27.78	190.63	35.23	181.59	31.44	132.39	1
	USGS 09277500	Beaver Divide	10.29	210.39	14.11	179.49	17.45	170.83	20.18	200.3	2
		Average	**16.70**	**223.50**	**20.90**	**185.10**	**26.30**	**176.20**	**25.80**	**166.40**	
3. Central & Southern	120,473	Castle Valley	12.23	244.05	16.96	203.04	22.22	187.68	26.30	180.00	1
Sevier near Hatch	USGS 10174500	Harris Flat	8.71	298.76	15.25	273.59	24.16	222.99	21.15	209.77	2
		Farnsworth Lake	17.25	218.10	20.96	185.95	27.05	182.24	32.93	167.03	3
		Average	**12.80**	**253.70**	**17.70**	**220.90**	**24.50**	**197.70**	**26.80**	**185.60**	
Coal Creek near Cedar City	38,533	Midway Valley	20.89	215.65	29.12	194.04	35.89	176.99	42.29	167.97	1
	USGS 10242000	Webster Flat	13.57	232.46	18.70	197.95	24.30	184.64	24.93	181.12	2
		Average	**17.20**	**224.10**	**23.90**	**196.00**	**30.10**	**180.90**	**33.60**	**174.60**	
South Willow near Grantsville	5,426	Rocky Basin-settlemnt	19.09	205.33	23.75	174.14	32.11	171.39	40.01	167.51	1
	USGS 10172800	Mining Fork	16.31	243.66	20.74	177.04	27.81	171.79	32.19	168.74	2
		Average	**17.70**	**224.50**	**22.30**	**175.60**	**30.00**	**171.60**	**36.10**	**168.10**	
Virgin River at Virgin	151,286	Kolob	23.11	229.25	29.08	220.78	36.51	197.43	43.71	196.21	1
	USGS 09406000	Harris Flat	9.71	377.00	15.69	304.18	21.46	300.00	20.11	370.00	2
		Midway Valley	24.76	256.17	34.56	238.40	41.44	209.68	51.05	211.06	3
		Long Flat	9.38	265.88	13.54	286.16	19.20	286.18	18.91	187.00	4
		Average	**16.70**	**282.10**	**23.20**	**262.40**	**29.70**	**248.40**	**33.40**	**241.10**	
Santa Clare above Baker Reservoir	11,620	Gardner Peak	13.00	293.90	16.82	172.15	21.70	167.36	24.45	163.95	1
	USGS 09409100	**Average**	**13.00**	**293.90**	**16.80**	**172.10**	**21.70**	**167.40**	**24.50**	**164.00**	
		Utah State Average (%)		**230**		**197**		**183**		**178**	
		Standard Deviation		**42**		**38**		**35**		**42**	
		Upper 95%		**248**		**213**		**199**		**196**	
		Lower 95%		**212**		**180**		**168**		**160**	

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. 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. There are a number of SNOTEL stations in the various basins of central and southern Utah on which these criteria are based. These include Castle Valley, Harris Flat, and Farnsworth Lake in the Sevier Basin; Midway Valley, Kolob, Harris Flat, Webster Flat, and Long Flat in southwestern Utah; and Rocky Basin Settlement and Mining Fork in eastern Tooele County.

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.

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.

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 which 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 Warning** - 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.
- **Severe Thunderstorm Warning** – This is issued by the NWS when thunderstorms producing winds of 58 mph or higher and/or 1” or larger hail.

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 and Severe Thunderstorm Warnings are usually issued when intense convective activity causing heavy rainfall/strong winds/hail 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 April. 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, 2022-2023
Storms 1-9

Storm	1	2	3	4	5	6	7	8	9
Dates	Nov 2-3	Nov 9	Nov 13	Nov 28-29	Dec 2	Dec 7	Dec 11-12	Dec 28	Jan 1-2
SITES									
TO1								7.5	
TO2				13.5					
TO3				13.5					
TO4				13.75					
TO5									
TO6									
TO7									
TO8									
TO9				15.5					
TO10									
TO11									
CU1				14					
CU2				13.75				7.5	
CU3				12.75			10.75		
CU4				13.75					
CU5				12.5			10.75	7.5	
CU6				12.75					
CU7				12.75				8	
CU8				8				11.75	
CU9									
CU10								7.5	
CU11				13.5				7.25	
CU12				12				7.25	
CU13								7.25	

Storm	1	2	3	4	5	6	7	8	9
Dates	Nov 2-3	Nov 9	Nov 13	Nov 28-29	Dec 2	Dec 7	Dec 11-12	Dec 28	Jan 1-2
SITES									
CU14				13.5			10	5	
CU15									
CU16								7.5	
CU17				13.25					
CU18							11		
CU19				13.25			11	7.5	
CU20				13			11	7.25	
CU21				11.25			11.5	7.5	
CU22	23	9.75					11.25		
CU23	23	8.25		12.25			9.5	7.25	
CU24	24	9.5		12				6.5	
CU25	22	9.25					11.5	7	
CU26	12							7	
CU27	23	9		12.5			12.75		
CU28	23.5	10					11	7.25	
SU1	4							18.75	
SU2	14					3.5		5.25	
SU4						3.25		4.5	
SU5		9						5.5	
SU6	23.25						12.5	4.5	
SU7	22	10					12.5	4.75	
SU8	6	7.5			4				
SU9	21.5	9			2.75		12.25	5	
SU11	22	8	5				15.75	6.25	18.75
SU12	22							6.5	
SU14	23.5	9.75						5	
SU15	24.25	8					12.75	4.25	
SU18	22.5	9.5					12.25		
SU19	22	9.75					12.25		
SU20	21	10					12.75	5.25	
SU21	22	9.75					12.5		

Storm	1	2	3	4	5	6	7	8	9
Dates	Nov 2-3	Nov 9	Nov 13	Nov 28-29	Dec 2	Dec 7	Dec 11-12	Dec 28	Jan 1-2
SITES									
SU22	22.5	10			3.5		12.5		
SU23	23.25				3.75		12.5		
SU24									
SU25		9.5					11.25		
SU26									
SU27		7.75					12.5		
SU28							12.5		
SU29	22	8.5							
SU30	22	9.5					12		
SU31									
SU32	20.75								
SU33							12.25		
SU34							12.25		
Storm Total	**531**	**201.25**	**5**	**283**	**14**	**6.75**	**349.25**	**216.75**	**18.75**
LBS Extension	**531**	**201.25**	**5**						

Table B-2
Generator Hours – Central and Southern Utah, 2022-2023
Storms 10-18

Storm	10	11	12	13	14	15	16	17	18
Dates	Jan 5-6	Jan 10-11	Jan 14-15	Jan 16	Jan 17	Jan 19-20	Feb 5-6	Feb 6	Feb 14
SITES									
TO1									
TO2									
TO3									
TO4	22								
TO5	19.75	13							
TO6									
TO7									
TO8	20	12.75							
TO9	19								
TO10	20.75	13.5							
TO11									
CU1									
CU2	19	14.25							
CU3	19								
CU4		14.25							
CU5	14.5	13.75							
CU6	19	13.25							
CU7		17.25		3.75					
CU8		11.25							
CU9									
CU10	19			0.75			4.25		
CU11	19	12.75					4.25		
CU12	14.5	13.5		3.75	4.25		4.25		
CU13		13.25		4	4.25		4.25		
CU14	11.75	15					6		
CU15							5.75		
CU16	18.75	15	9				5.75		
CU17	19.5		10.75				5.75		

Storm	10	11	12	13	14	15	16	17	18
Dates	Jan 5-6	Jan 10-11	Jan 14-15	Jan 16	Jan 17	Jan 19-20	Feb 5-6	Feb 6	Feb 14
SITES									
CU18		14.5	11.25				5.75		
CU19			11						
CU20	20	17.75							
CU21							4.75		
CU22	18.25	12.75	11.25				5.25		
CU23	18						5.5		
CU24		12.5					5.5		
CU25									
CU26							4.75		
CU27	18.25						5.5		
CU28	18.25	10.5					5.5		
SU1		14.25							
SU2		13.75		7	4.5				6
SU4	17.5		24.25	6.75					5.5
SU5									5.5
SU6	19								
SU7	17.5		24		4.25			5.5	5.5
SU8	17.75				4.25		5.25	5.25	
SU9	17.25		24.25		3.5			1.75	2.5
SU11	19	14.5		3		16.25	17.75	4.5	5.5
SU12	19	14.25	24.75			15.25	5	5.25	6.5
SU14	17.5		24.5	7.25	4.5				5.75
SU15	18		24.75	7.25	4	12.75	4.75		5.75
SU18		13.25					4.5	5.25	
SU19	20								
SU20	14.25		24				4.25		
SU21	18.75	13.5	24.5						
SU22	18.75								
SU23	19		24.75			12.75	4.75	5.25	5.5
SU24									
SU25	17.5								5.25

Storm	10	11	12	13	14	15	16	17	18
Dates	Jan 5-6	Jan 10-11	Jan 14-15	Jan 16	Jan 17	Jan 19-20	Feb 5-6	Feb 6	Feb 14
SITES									
SU26									
SU27	18.75								
SU28	17.5		22.75						
SU29		13.75							
SU30									
SU31									
SU32	18.75		24.5						
SU33	19.25	13.5							
SU34	18.25		24.5						5.25
Storm Total	**731.5**	**384**	**344.75**	**43.5**	**33.5**	**57**	**129**	**32.75**	**64.5**
LBS Extension									

Table B-3
Generator Hours – Central and Southern Utah, 2022-2023
Storms 19-27

Storm	19	20	21	22	23	24	25	26	27
Dates	Feb 21-22	Feb 23-24	Feb 27-28	Feb 28-Mar 1	Mar 5-6	Mar 8	Mar 19-20	Mar 20	Mar 21-22
SITES									
TO1	19.75					7.25			
TO2	17.25				12	6			
TO3	17.5				12	6			
TO4					12	7			
TO5	17.25				11.75	7			
TO6	15.75				11.75	7			
TO7									
TO8	20				11.75	7			
TO9	22.75				11.5	6			
TO10	18.25				10.25	6.75			
TO11	19.5					6.75			
CU1						5.75			
CU2						5.75			
CU3						5.75			
CU4									
CU5									
CU6						3.5			
CU7						5			
CU8									
CU9						5.25			
CU10						5.5			
CU11						5.25			
CU12						5.25			
CU13						5			
CU14						4			
CU15						4			
CU16									

Storm	19	20	21	22	23	24	25	26	27
Dates	Feb 21-22	Feb 23-24	Feb 27-28	Feb 28-Mar 1	Mar 5-6	Mar 8	Mar 19-20	Mar 20	Mar 21-22
SITES									
CU17						4			
CU18						4			
CU19						4			
CU20							14		
CU21							14		
CU22						4	14		
CU23						4	14		
CU24							14		
CU25							13.25		
CU26							14		
CU27									
CU28							14		
SU1			13.75	10.25					
SU2			13.75						
SU4		16.5	14.5	21					
SU5		16.5	14.5	23					
SU6								8.5	
SU7								8.75	
SU8				20.5				8.75	
SU9				21				6.25	
SU11				24			16.5	6.25	16.5
SU12		15.5	13.5				15		
SU14			6.75						
SU15				22.25					
SU18							14		
SU19									
SU20				20.75			14.5		
SU21				21			14		15.5
SU22							14		
SU23				21.25			15.5		15
SU24									

Storm	19	20	21	22	23	24	25	26	27
Dates	Feb 21-22	Feb 23-24	Feb 27-28	Feb 28-Mar 1	Mar 5-6	Mar 8	Mar 19-20	Mar 20	Mar 21-22
SITES									
SU25		15		19.75					
SU26									
SU27									
SU28		16.75		15.5					
SU29							14	5.75	14.75
SU30							14	19	
SU31									
SU32				21			14		14.75
SU33				21			14		
SU34		15.75		22.25				6.5	14.5
Storm Total	**168**	**96**	**76.75**	**304.5**	**93**	**146.75**	**270.75**	**69.75**	**91**
LBS Extension							**270.75**	**69.75**	**91**

Table B-4
Generator Hours – Central and Southern Utah, 2022-2023
Storms 28-30

Storm	28	29	30	Site Totals
Dates	Mar 24	Mar 30	Apr 3-4	
SITES				
TO1				27
TO2				56.25
TO3				49
TO4				54.75
TO5				68.75
TO6				34.5
TO7				0
TO8				74.5
TO9				74.75
TO10				70.5
TO11				26.25
CU1				19.75
CU2				60.25
CU3				48.25
CU4				28
CU5				59
CU6				48.5
CU7				46.75
CU8				31
CU9				5.25
CU10				37
CU11				62
CU12				64.75
CU13				38
CU14		8	19.75	93
CU15		8		17.75
CU16	6.75	8	19.5	90.25

Storm	28	29	30	Site Totals
Dates	Mar 24	Mar 30	Apr 3-4	
SITES				
CU17				53.25
CU18	6.75			53.25
CU19	6.75	8	19.5	81
CU20	6.25	7.75	18.25	115.25
CU21	6.75		19.5	75.25
CU22		7.75	18.75	136
CU23	6.5	7.75		116
CU24	6.5	7.75		98.25
CU25	6.5			69.5
CU26	6.5	7.75		52
CU27				81
CU28	6.5	7.75	19.25	133.5
SU1				61
SU2				67.75
SU4				113.75
SU5				74
SU6				67.75
SU7		7.5		122.25
SU8				79.25
SU9		7		134
SU11				219.5
SU12		7.5		170
SU14				104.5
SU15				148.75
SU18		7.25	19.25	107.75
SU19			19.25	83.25
SU20		6.75	19	152.5
SU21				151.5
SU22		7.25	19	107.5
SU23				163.25

Storm	28	29	30	Site Totals
Dates	Mar 24	Mar 30	Apr 3-4	
SITES				
SU24				0
SU25				90.75
SU26				0
SU27				39
SU28				85
SU29		7	19.25	105
SU30		7	14	97.5
SU31				0
SU32		7.5		121.25
SU33		7.5		87.5
SU34			15.75	135
Storm Total	**65.75**	**150.75**	**260**	
LBS Extension	**65.75**	**150.75**	**260**	

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

Primary Target Linear Regression
Dec-Mar Precipitation

Non-seeded period:

Year	Control	Target	Predicted	Ratio	Increase
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
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
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	7.2	9.2	8.9	1.03	0.3
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	8.6	7.2	1.20	1.4
2019	10.9	15.7	15.2	1.03	0.5
2020	8.0	10.1	10.4	0.98	-0.2
2021	6.8	9.3	8.4	1.12	1.0
2022	6.4	11.0	7.6	1.44	3.4
2023	13.1	16.3	19.0	0.86	-2.7
Mean	8.3	12.1	10.9	1.112	1.2

*Seeding conducted in adjacent areas, but not target area

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.955721**
R Square	**0.913403**
Adjusted R Square	0.907991
Standard Error	0.901939
Observations	18

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Upper 95.0%*
Intercept	**-3.173422**	1.173074	-2.705219	0.015604	-5.660227	-0.68662	-0.68662
X Variable 1	**1.688715**	0.129992	12.99091	6.46E-10	1.413144	1.964286	1.964286

Eastern Tooele Target Linear Regression
Dec-Mar Precipitation

Non-seeded period

Year	Control	Target	Predicted	Ratio	Increase
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
Mean	14.0	11.6	11.6	1.00	0.0

Seeded period:

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	18.5	17.3	15.5	1.11	1.8
2020	10.6	8.4	8.6	0.98	-0.2
2021	11.1	9.4	9.0	1.04	0.4
2022	10.4	8.3	8.4	0.99	-0.1
2023	18.3	24.3	15.3	1.59	9.1
Mean	13.5	12.6	11.1	**1.13**	**1.5**

* Seeding in other parts of Utah but not target area, so excluded from the mean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.782368**
R Square	**0.612099**
Adjusted R Square	0.59718
Standard Error	2.231851
Observations	28

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	**-0.69476**	1.959753	-0.354514	0.725813	-4.72309	3.33357	-4.72309	3.33357
X Variable 1	**0.875061**	0.136616	6.405266	8.73E-07	0.594243	1.15588	0.594243	1.15588

Primary Target
Apr 1 Snow Water Content Linear Regression

Non-seeded period:

Year	Control	Target	Predicted	Ratio	Increase
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	8.8	12.3	0.72	-3.5
1973	21.6	20.7	21.9	0.94	-1.2
1984	23.8	24.1	24.2	0.99	-0.2
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
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
2022	8.5	10.6	8.4	1.26	2.2
2023	25.8	20.5	26.3	0.78	-5.8
Mean	14.0	14.6	14.1	1.035	0.5

* Seeding conducted in adjacent areas but not target area, so not included in mean

** Results not included in mean due to early snowmelt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.935556396
R Square	0.87526577
Adjusted R Square	0.867928462
Standard Error	1.740763607
Observations	19

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Upper 95.0%*
Intercept	- 0.378966405	1.483944	-0.25538	0.801495	- 3.50982	2.751883	2.751883

X Variable 1	1.035560851	0.094814	10.92199	4.19E-09	0.83552	1.235602	1.235602

Primary Target

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

Non-seeded period:

YEAR	North Ctrl	South Ctrl	YOBS	YCALC	RATIO	EXCESS
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	8.8	11.3	0.78	-2.5
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
Mean	18.5	11.6	15.2	15.2	1.00	0.0

Seeded Period:

YEAR	North Ctrl	South Ctrl	YOBS	YCALC	RATIO	EXCESS
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
1988	13.5	7.4	13.1	10.3	1.27	2.8
1989	20.7	8.3	11.3	13.9	0.81	-2.7
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
2022	10.3	6.7	10.6	8.5	1.24	2.1
2023	28.9	22.7	20.5	26.9	0.76	-6.4
Mean	16.7	11.3	14.6	14.3	1.025	0.4

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

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.949996055
R Square	0.902492504
Adjusted R Square	0.890304067
Standard Error	1.586464815
Observations	19

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Upper 95.0%*

	-						
Intercept	**0.260923565**	1.353562	-0.19277	0.849566	-3.13035	2.6085	2.6085
North Ctrl	**0.417766179**	0.064075	6.519931	7.06E-06	0.281933	0.5536	0.5536
South Ctrl	**0.666458753**	0.08255	8.073371	4.93E-07	0.49146	0.841457	0.841457

Eastern Tooele Target
Apr 1 Snow Water Content

Regression (non-seeded) period:

Year	Control	Target	Predicted	Obs/Pred Ratio	Increase
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
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
Mean	15.5	15.8	15.8	1.00	0.0

Seeded period:

Year	Control	Target	Predicted	Obs/Pred 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
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
2022*	8.4	5.4	8.2	0.66	-2.8
2023	26.3	29.7	27.3	1.09	2.4
Mean	13.3	14.7	13.4	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%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.80605	2.774503	-0.29052	0.773637	-6.49886	4.886756	-6.49886	4.886756
X Variable 1	1.068717	0.172081	6.210555	1.22E-06	0.715637	1.421798	0.715637	1.421798

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.

Precipitable Water, or PWAT: The total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between the surface and top of the atmosphere, expressed in terms of the depth to which that water substance would be if completely condensed and collected in a vessel of the same unit cross-section.

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. Mountain Standard Time (MST) = GMT – 7 hours; Mountain Daylight Time (MDT) = GMT – 6 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