Annual Cloud Seeding Report

Southern & Central Utah Program

2023-2024 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

North American Weather Consultants, Inc.

8180 S. Highland Dr., Suite B-2

Sandy, Utah 84093

July 2024

Table of Contents

EXECUTIVE SUMMARY i
CLIMATE TRENDS iii
1.0 INTRODUCTION 1
1.1 Core Program and Extension Periods 2
2.0 PROJECT DESIGN 3
2.1 Background 3
2.2 Seedability Criteria 3
2.3 Equipment and Project Set-Up 4
2.4 Suspension Criteria 10
3.0 WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS 11
4.0 OPERATIONS 20
4.1 Operational Procedures 26
4.2 Operational Summary 26
5.0 ASSESSMENTS OF SEEDING EFFECTS 40
5.1 Background 40
5.2 Evaluation Approach 41
5.3 Evaluation of Precipitation in the Target Area 42
5.4 Snow Water Equivalent (SWE) Evaluations 46
5.5 Summary of Evaluation Results 49
5.6 Determining the Impact of Cloud Seeding on Streamflow 50
REFERENCES 52
APPENDIX A SUSPENSION CRITERIA 54
APPENDIX B SEEDING OPERATIONS TABLES 59
APPENDIX C EVALUATION TARGET AND CONTROL SITES 72
APPENDIX D GLOSSARY OF RELEVANT METEOROLOGICAL TERMS 77

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. For the 2023-24 season, the Southern and Central Utah Seeding Program utilized 62 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 resulted in a late season (March 16th - April 15th) extension to the seeding program; normally, there is also an early-season extension, but this was not implemented for the 2023-24 season.

Precipitation and snowfall were above normal during the 2023-24 winter season (Southwestern Utah saw slightly below average seasonal precipitation.) A total of 3768.25 CNG hours were conducted during 24 storm periods for the core program this season. An additional 285.25 hours of seeding were conducted during five late-season storm periods for the Lower Basin Extension periods. **A brief suspension of operations for areas affecting Panguitch Lake was enforced in early April, just prior to the end of the season due to a potential dam breach.**

Evaluations of the effectiveness of the cloud seeding program were made for all seeded seasons combined. These evaluations utilized SNOTEL records collected by the Natural Resources Conservation Service (NRCS) at selected sites within and surrounding the seeded target areas and suggest increases of 0.5-1.5 inches of SWE for the target areas. For this season, a different approach to evaluating the effectiveness of the program was added; the effect of seeding on precipitation and snowpack with regards to streamflow and runoff were analyzed and are presented in the evaluation section of the report. Analyses from several streamflow gauge sites in the target areas suggested that potential seasonal streamflow increases of 5-13% could be obtained as a result of the seeding program and are discussed in Section 5 of the report.

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.

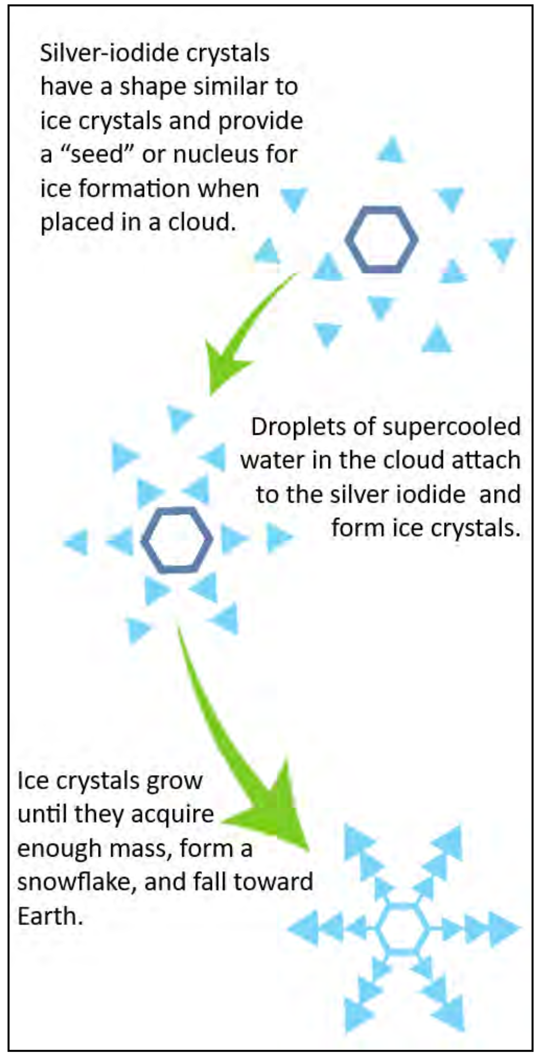
WEATHER MODIFICATION

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.

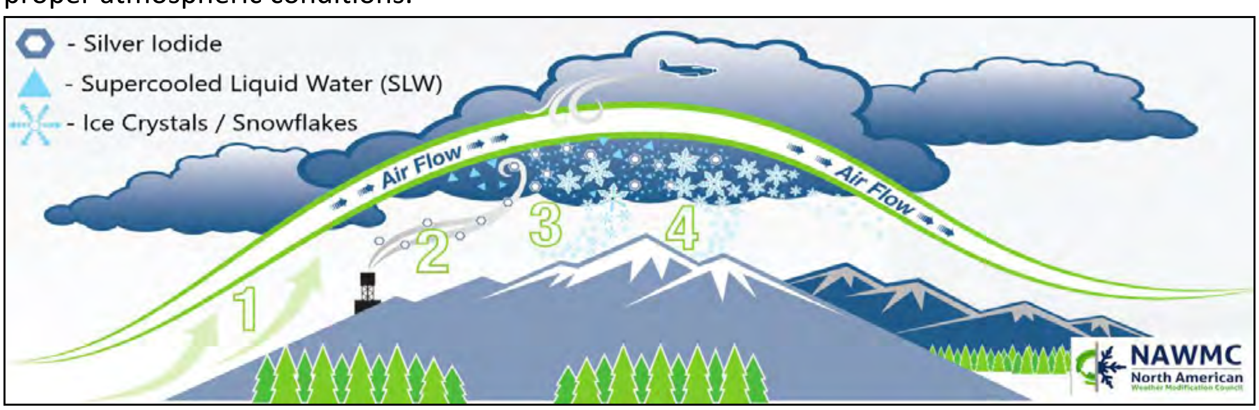


Safety

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.



CLIMATE TRENDS

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 Figures 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 3 shows the current 30-year average precipitation amounts for Utah based on 1991-2020 precipitation records.

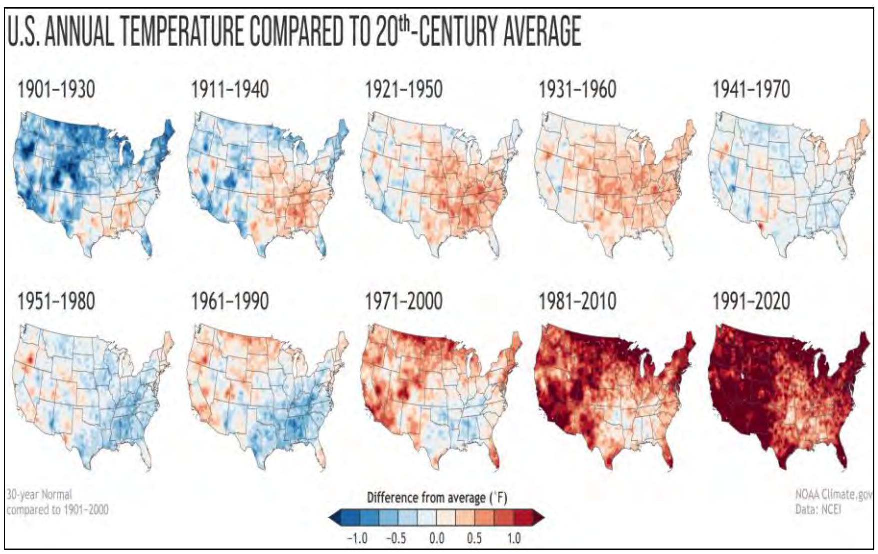


Figure 1. **U.S. Annual Temperature compared to 20th-Century Average**

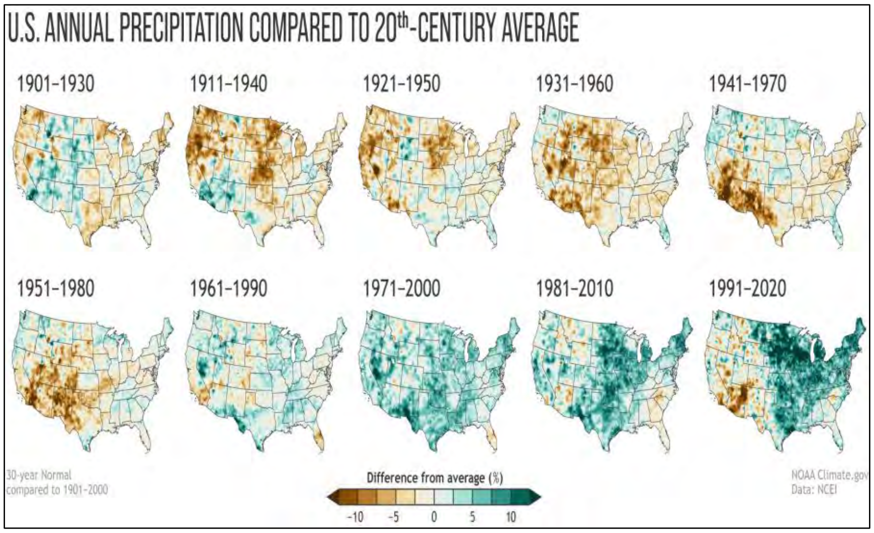


Figure 2. **U.S. Annual Precipitation compared to 20th-Century Average**

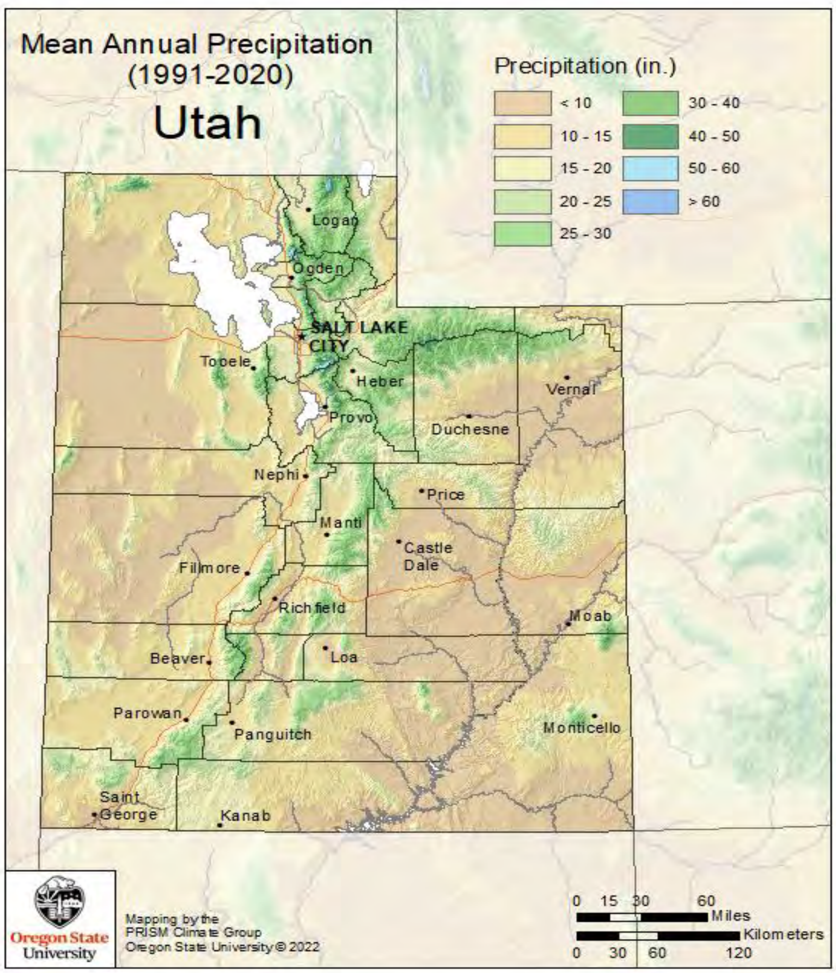


Figure 3. **Utah average annual precipitation based on 30-year averages from 1991-2020.**

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.

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.

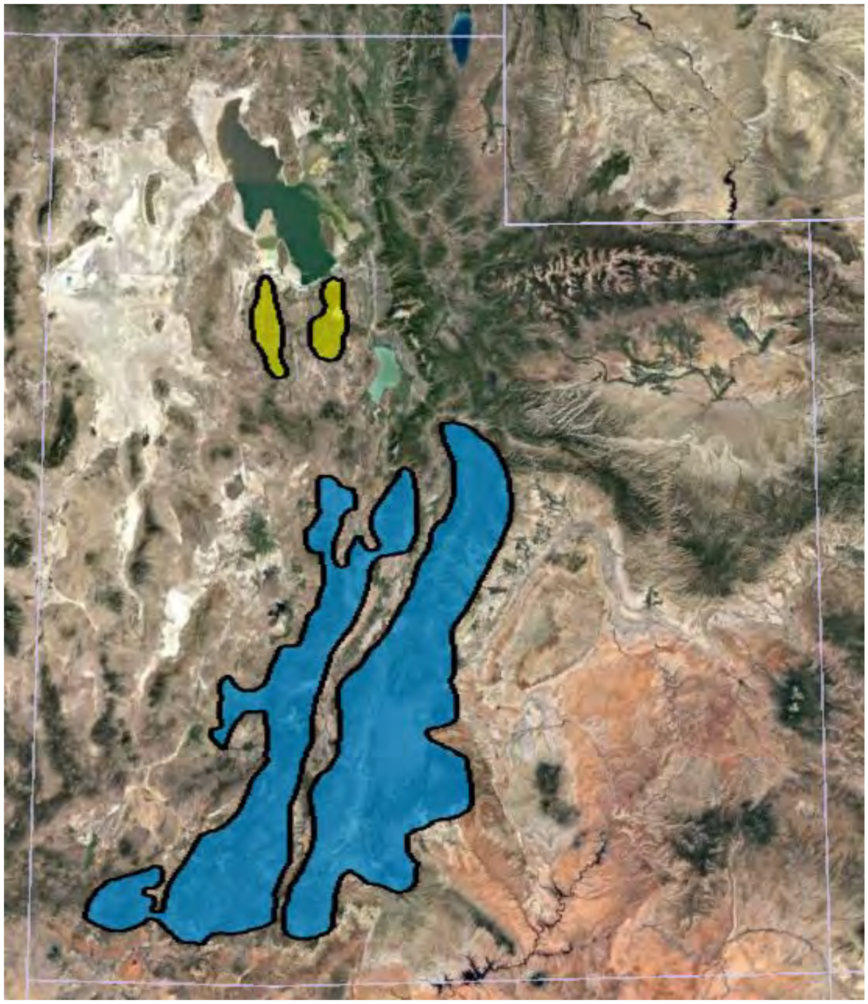


Figure 1.1. Seeded target areas in central and southwestern Utah; Eastern Tooele Target (yellow) and Primary Target (blue)

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 and 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 15 – March 15 this season. The Central/Southern Utah Project was one of two Utah projects selected to receive supplemental Lower Basin funding. For the 2023-24 season, only one extension period was funded by the Lower Basin States and Utah's Division of Water Resources, from March 16 – April 15. Near the end of the season, a temporary suspension area was imposed on all operations that would affect Panguitch Lake in southwestern Utah due to the risk of a dam failure at Panguitch Lake.

2.0 PROJECT DESIGN

2.1 Background

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

2.2 Seedability Criteria

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. In meteorology, winds are reported from the direction with which the winds are blowing. For example, a southwesterly wind means the winds are blowing from the southwest towards the northeast.

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 2023, following a period of off-season maintenance, NAWC technicians re-installed the ground-based cloud nuclei generators (CNGs) 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. There are 62 CNG site locations for the program. Information on these locations is provided in Table 2-1.

Ten (10) 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. A map of these sites and target areas is shown in Figure 2.1.

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

For this portion of the program, there are 52 CNG site locations. The target areas and site locations are shown in Figure 2.2.

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-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-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
CU-29	Kesko Ranch	39°23.90’	111°34.77’	5505
SU-1	Newcastle	37°40.61'	113°33.73'	5242

Site Number	Name	Latitude (N)	Longitude (W)	Elevation (feet)
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-7	Parowan	37°50.88'	112°49.56'	5980
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-23	Panguitch Lake	37°42.39'	112°38.47'	8255
SU-23	Alton	37°26.63’	112°31.22’	7300
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-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

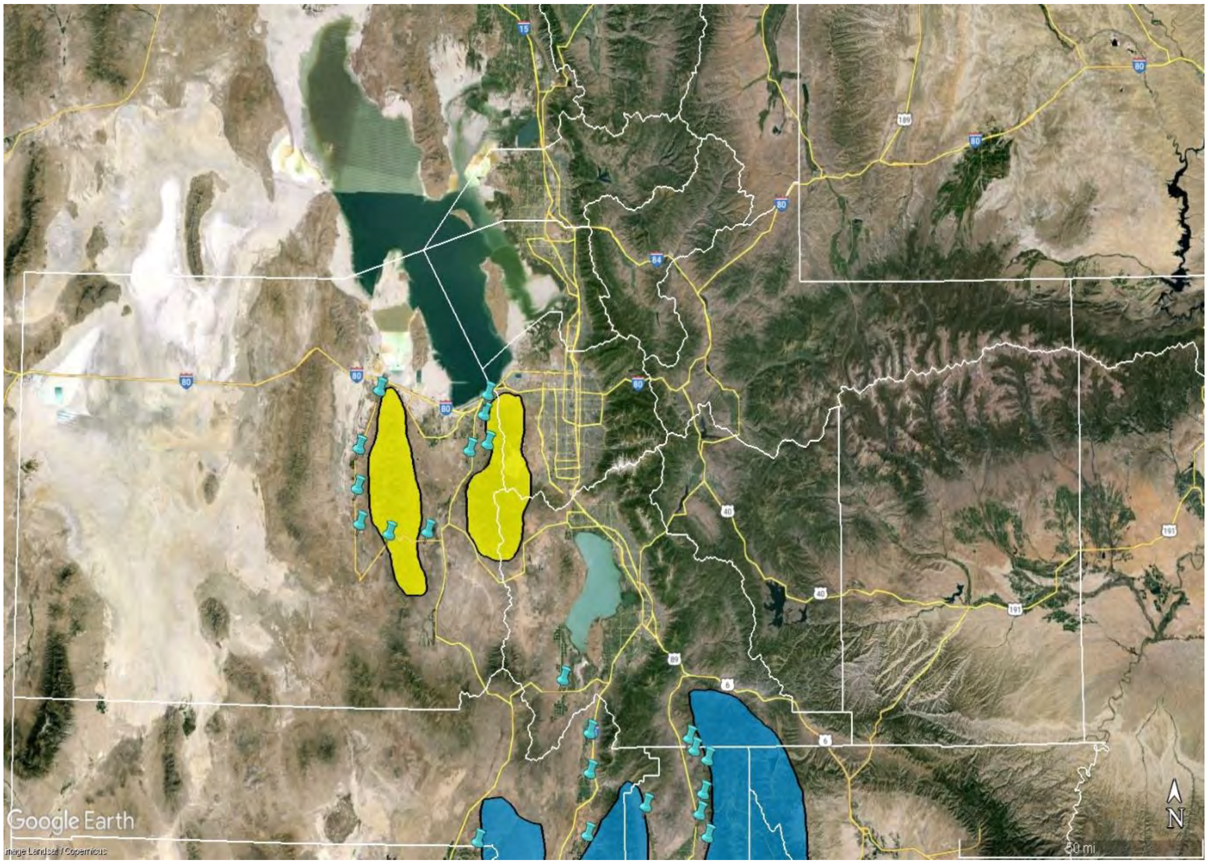


Figure 2.1. **Tooele County target areas and CNG locations.**

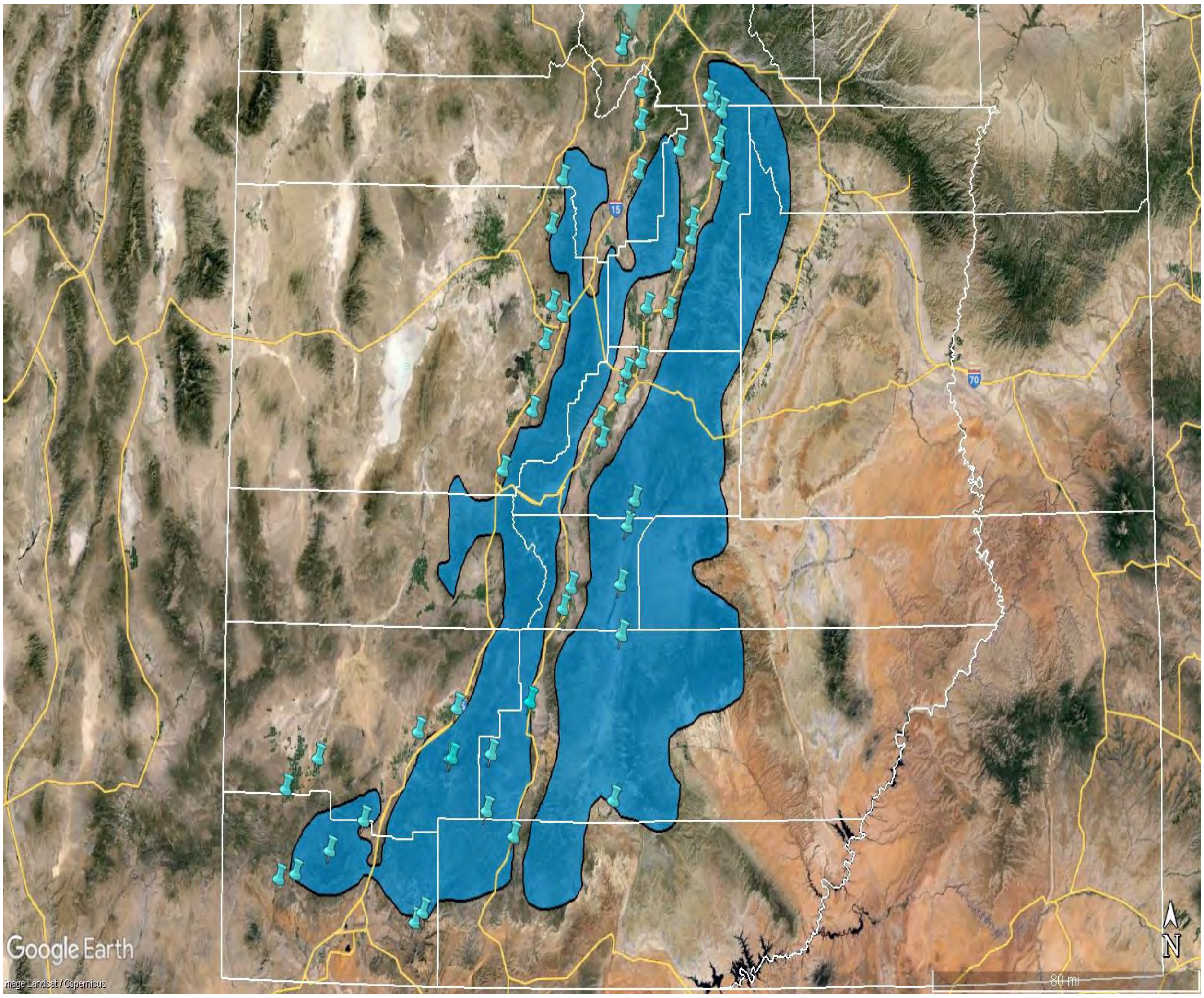


Figure 2.2. Primary Target area and CNG locations.

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 52 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 nuclei generator (CNG) 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 forces the solution through a spray nozzle into the burn chamber. As the seeding solution is sprayed into the propane flame, 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°C 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.

The core 2023-24 cloud seeding program for central and southern Utah began on November 15, 2023, and ended on March 15, 2024. The extension period funded by the Lower Basin States and Utah's Division of Water Resources, ran from 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 and Antimony. 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 2.3 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 2.3. **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 2023-24 season, there was one brief suspension placed on areas that would impact runoff into Panguitch Lake; on April 10, it was discovered that the Panguitch Lake Dam was at risk of failing, so any operations that might impact runoff into Panguitch Lake were halted until the risk of dam failure had passed. This only affected the final five days of the program.

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 – 3.6 show examples of some of the available weather information that was used in this decision-making process during the 2023-24 winter season. These include weather radar images, satellite images, upper air wind and temperature maps, rawinsonde/weather balloon soundings, surface observations and hazards such as lightning. 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 3.7). 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)**.

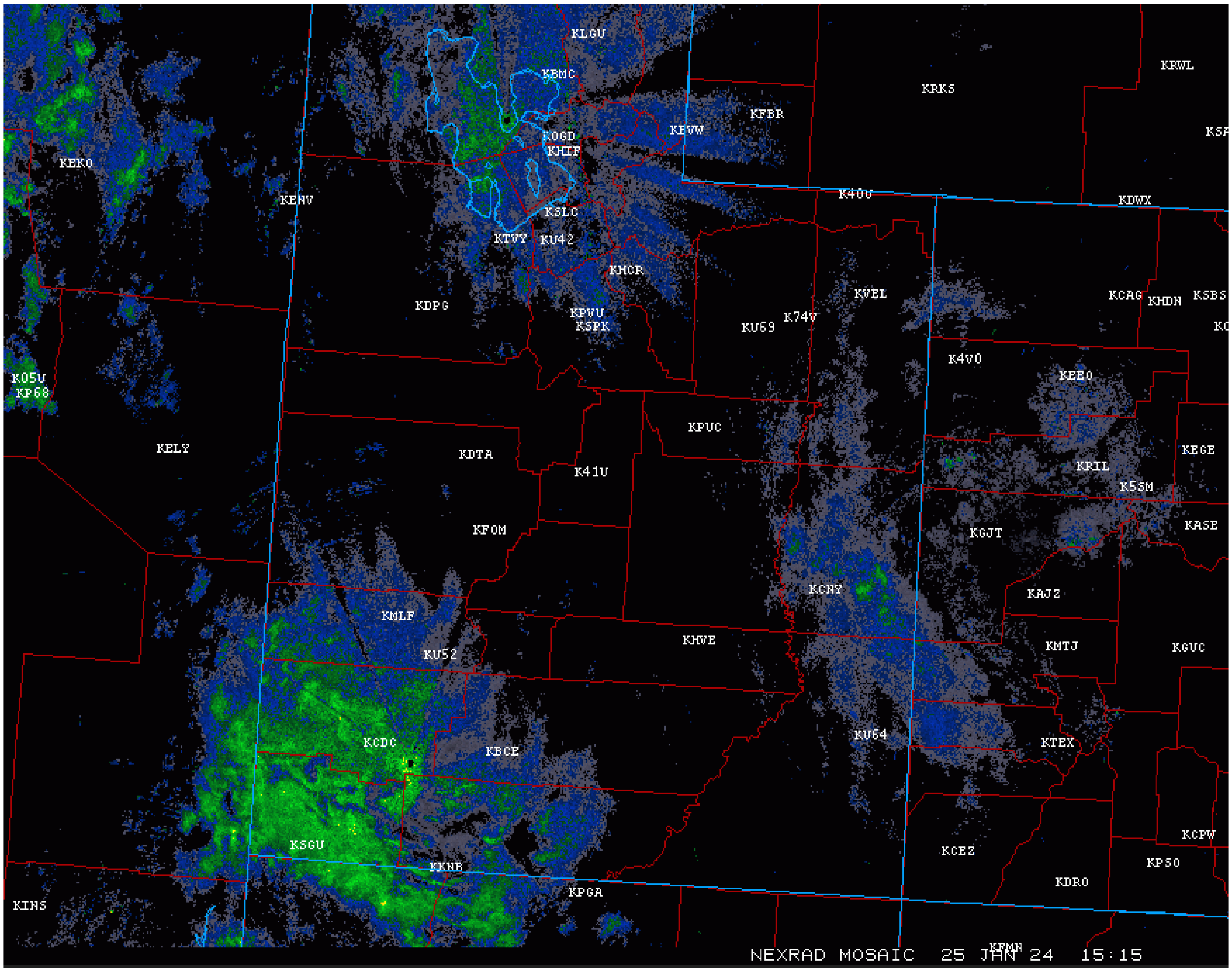


Figure 3.1. **Weather radar image during a storm event over southwestern Utah on January 25, 2024.**

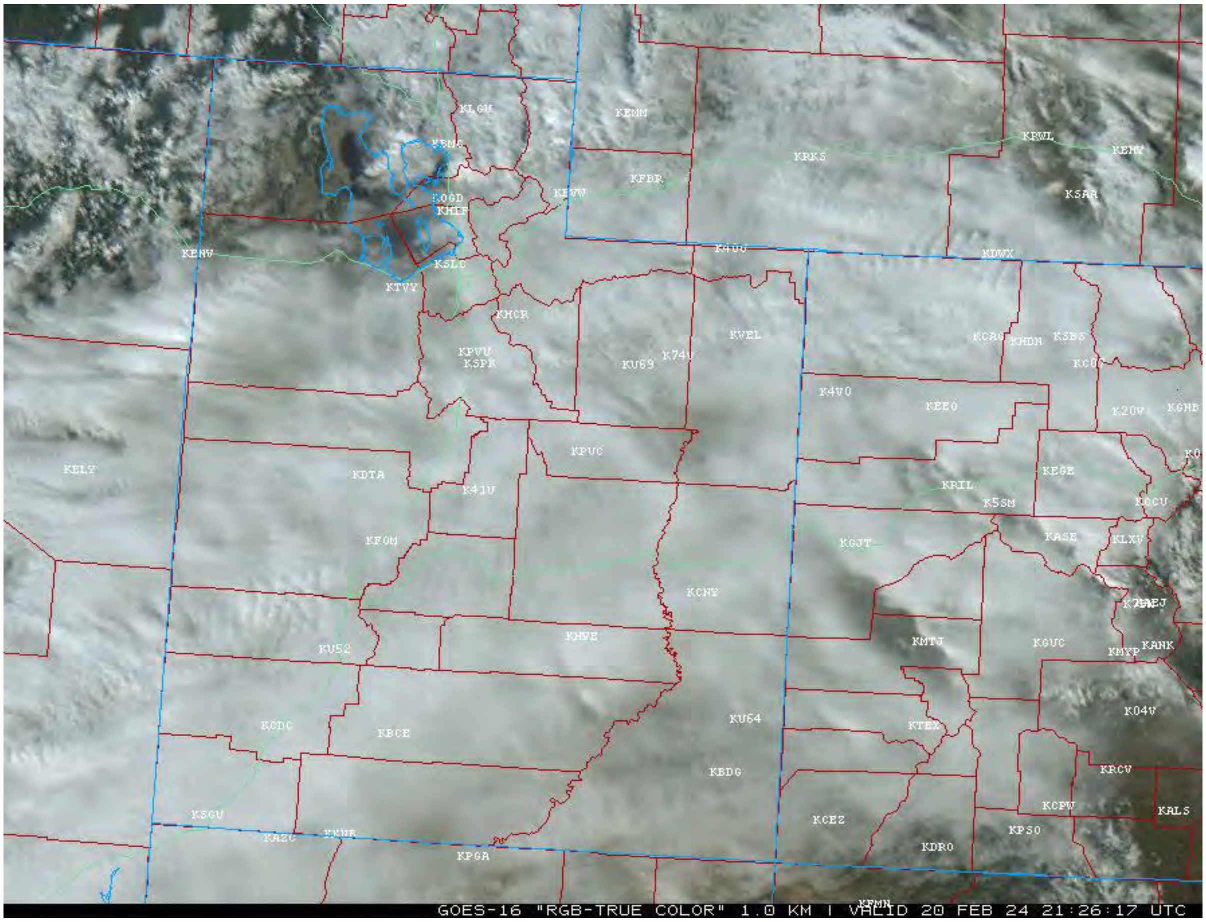


Figure 3.2. **Visible spectrum satellite image on February 20, 2024 at 1426 MST (2126 UTC).**

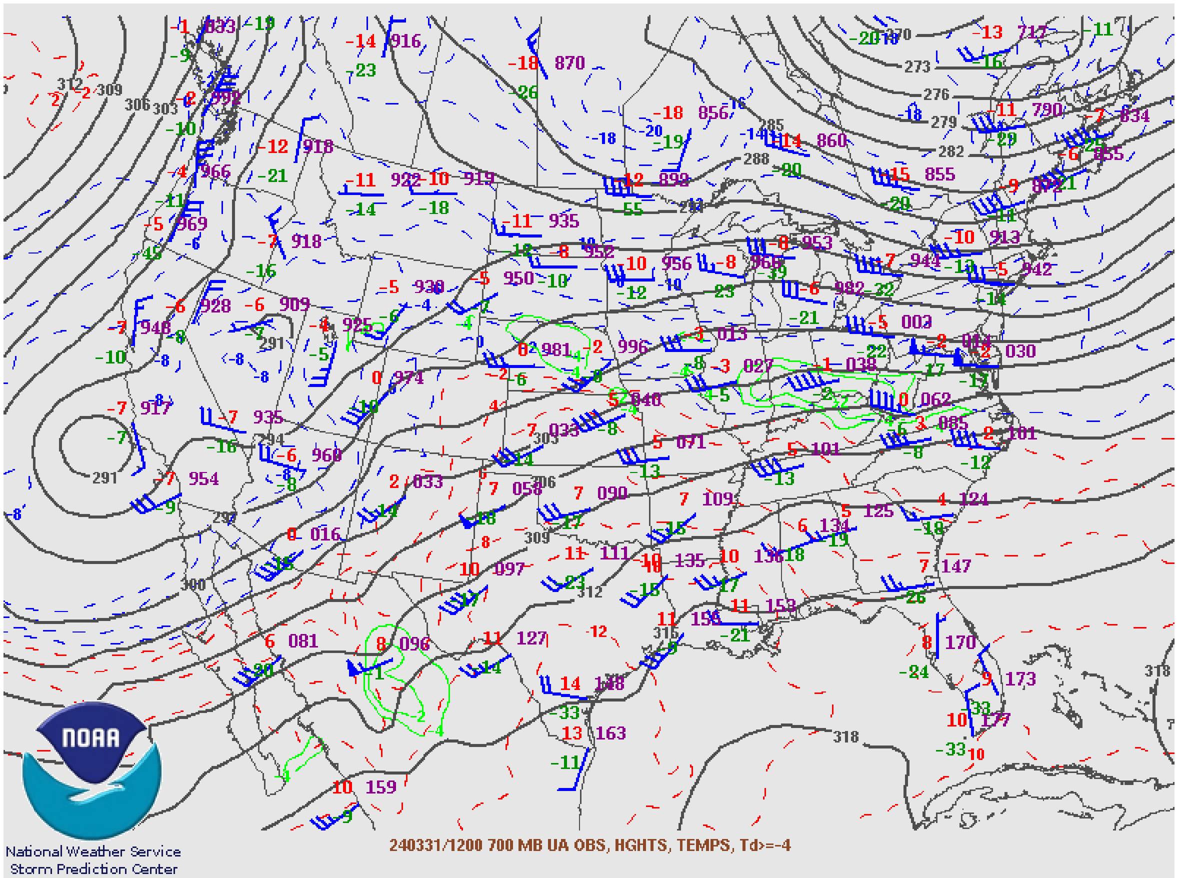


Figure 3.3. **700 mb (approximately 10,000 feet MSL) map valid for 1700 MST (0000 UTC) on March 30, 2024. Among the more notable map features, contours indicate heights (in decameters) of 700 mb pressure level, red numbers are temperature (°C), green numbers are dewpoints (°C), blue lines with barbs/flags represent wind speed and direction.**

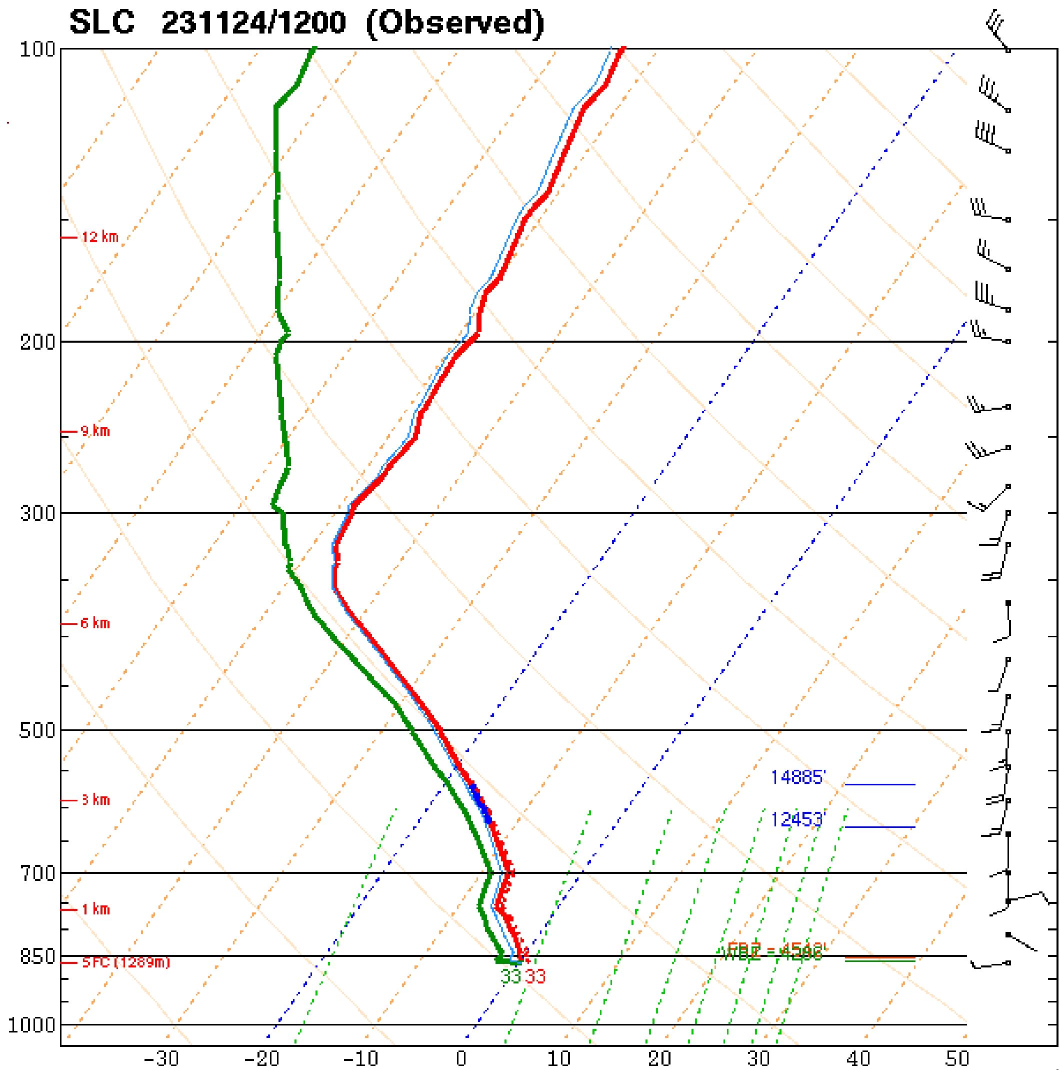


Figure 3.4. **Weather balloon/rawinsonde sounding from Salt Lake City, valid at 12Z/0500 MST on November 24, 2023 showing temperature (red line), dewpoint (green line) and wind speed/direction (right side barbs) from the surface to 100 mb (approximately 52,000 feet MSL).**

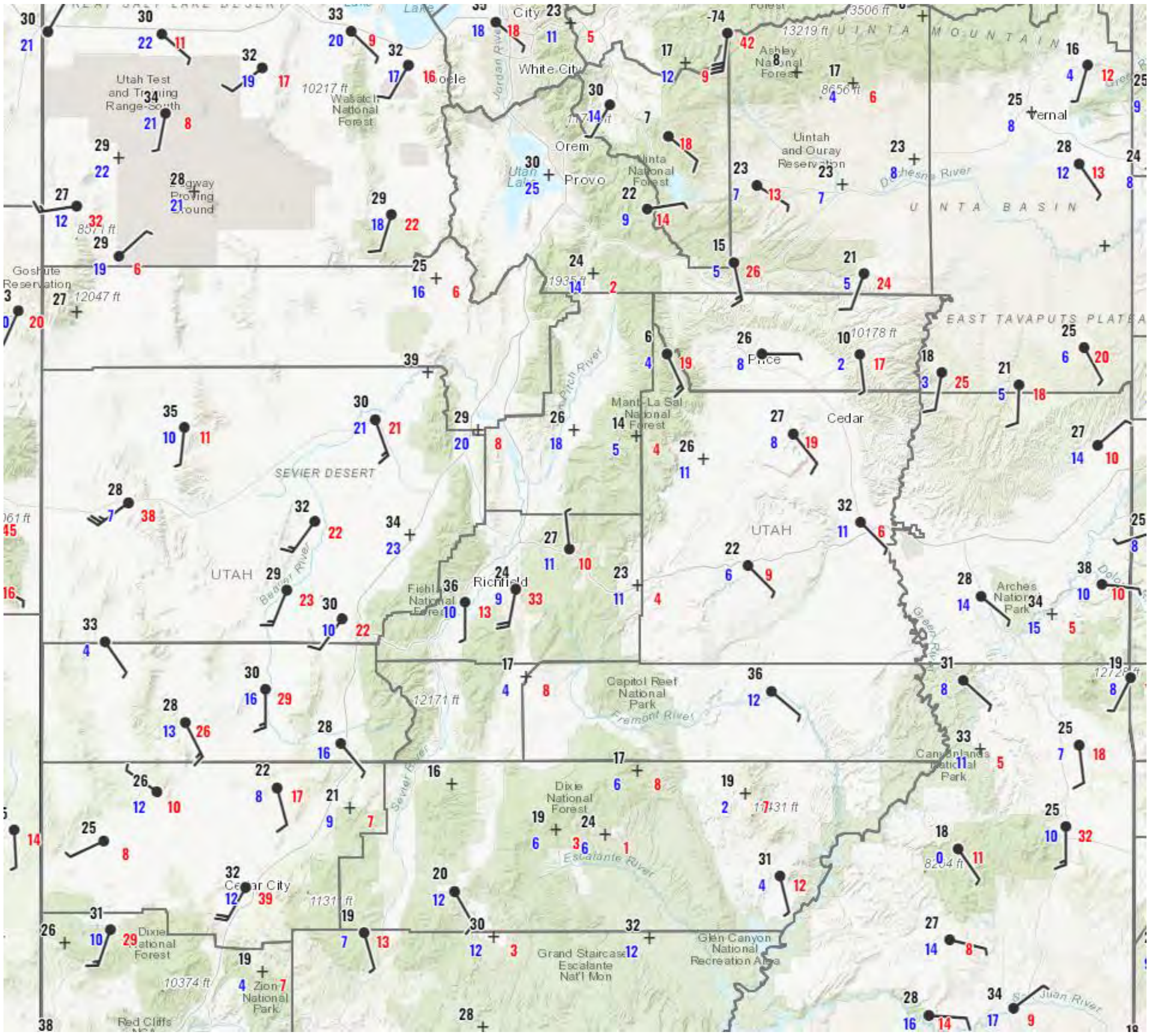


Figure 3.5. **MesoWest surface map from January 6, 2024 at 2000 MST. Black numbers are temperature, blue numbers are dew point, red numbers are wind gusts, and lines with barbs extending from sites indicate wind direction and speed. Courtesy of National Weather Service.**

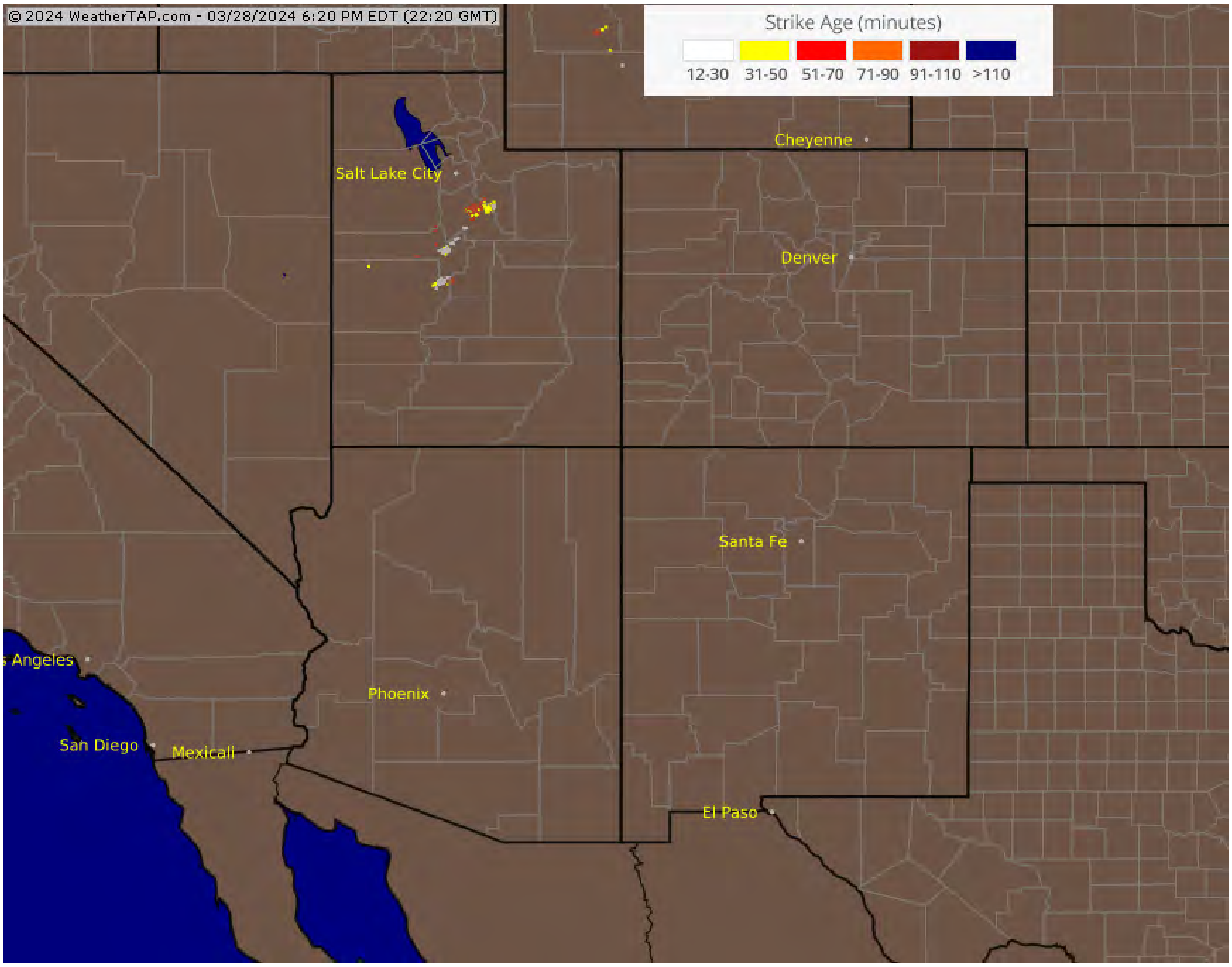


Figure 3.6. **Map showing recent lightning strikes across western United States on March 28, 2024 at 1620 MDT (2220 UTC). Legend shows age of lightning strike via color-coded dots. Courtesy of WeatherTap website, https://www.weathertap.com/ .**

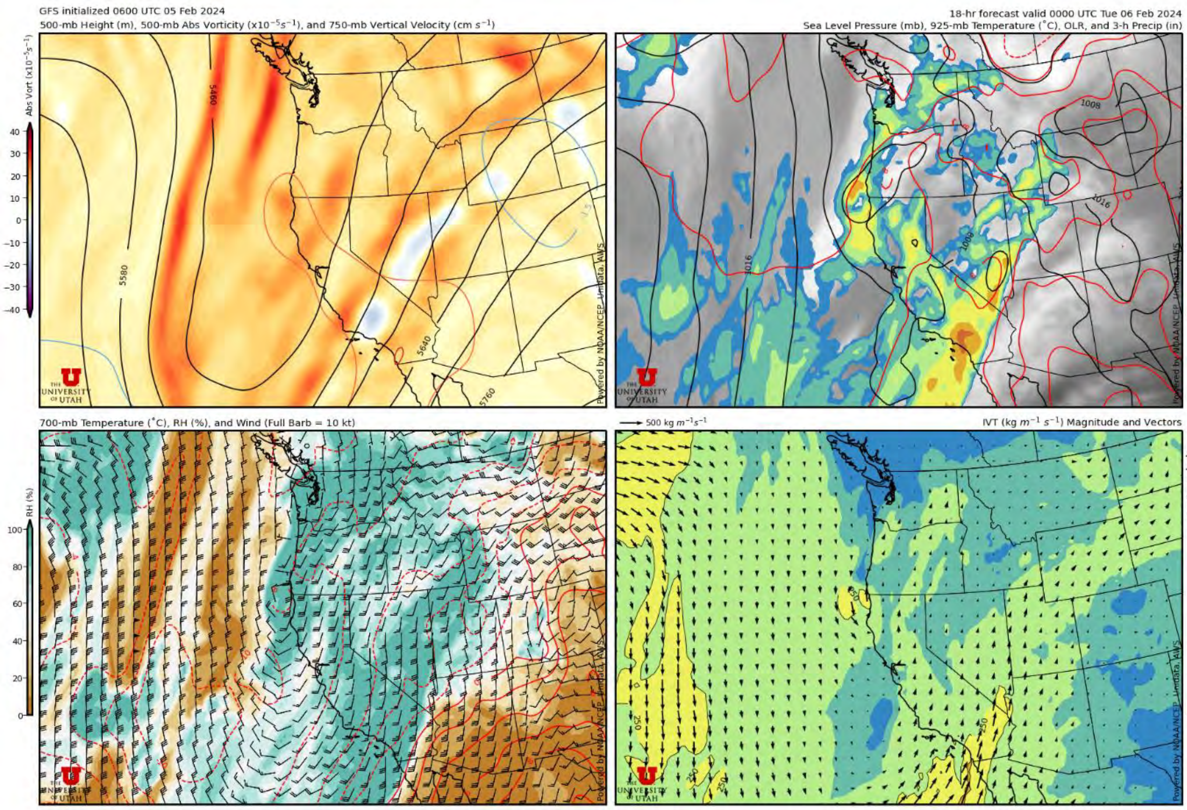


Figure 3.7. **GFS (Global Forecast Systems) forecast data plot for an approaching storm event on February 5, 2024.**

Figure 3.8 provides an example of 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. 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 and temperature profiles contained in the weather forecast models.

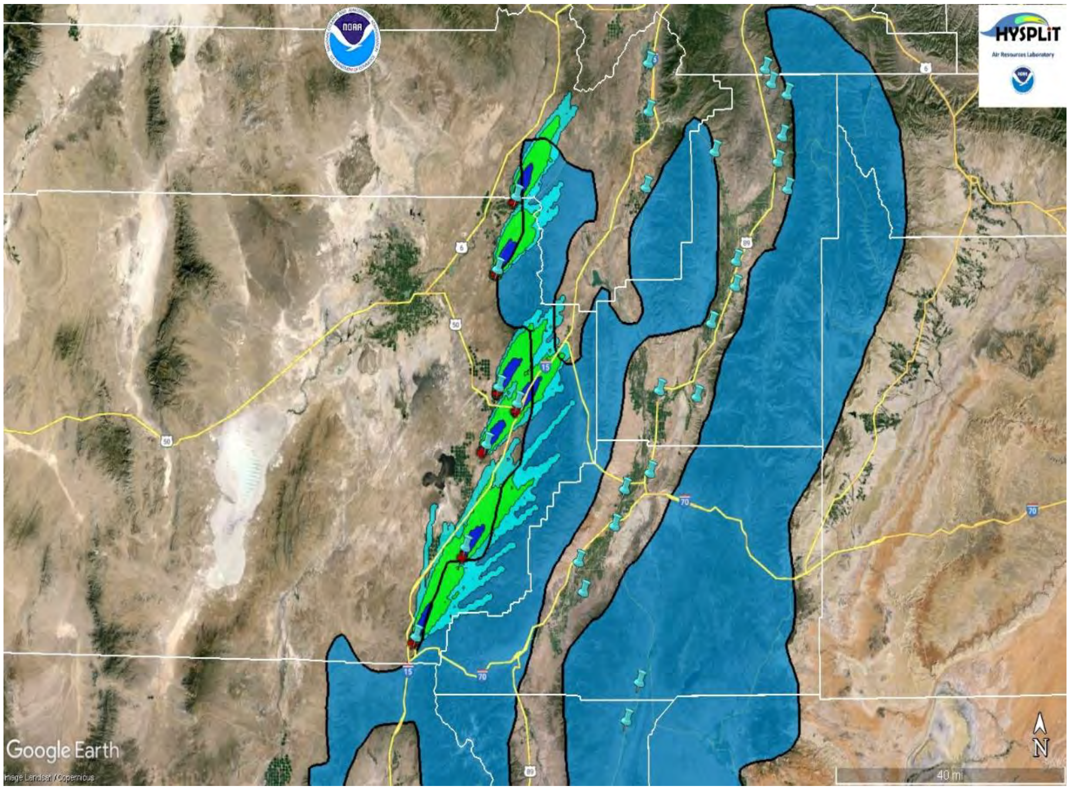


Figure 3.8. **HYSPLIT 1-hour plume dispersion forecast for CNG sites along I-15 corridor in Millard County from a storm event on January 6, 2024, valid at 2100 MST.**

4.0 OPERATIONS

A total of 29 storm events were seeded during the main core program contract period (November 15 – March 15) and five events were seeded during the latter extension period (March 15 – April 15). In all, there were two seeded storm events in November, three events in December, eight in January, seven in February, eight in March, and one in April. For the regular contract period, a cumulative 3768.25 generator hours were utilized. For the Lower Basin extension, there was an additional 285.25 generator hours of seeding conducted in the March 15-April 15 period. Figure 4.1 shows cumulative seeding hours for the core program this season with the extension period of March 16 – April 15 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.

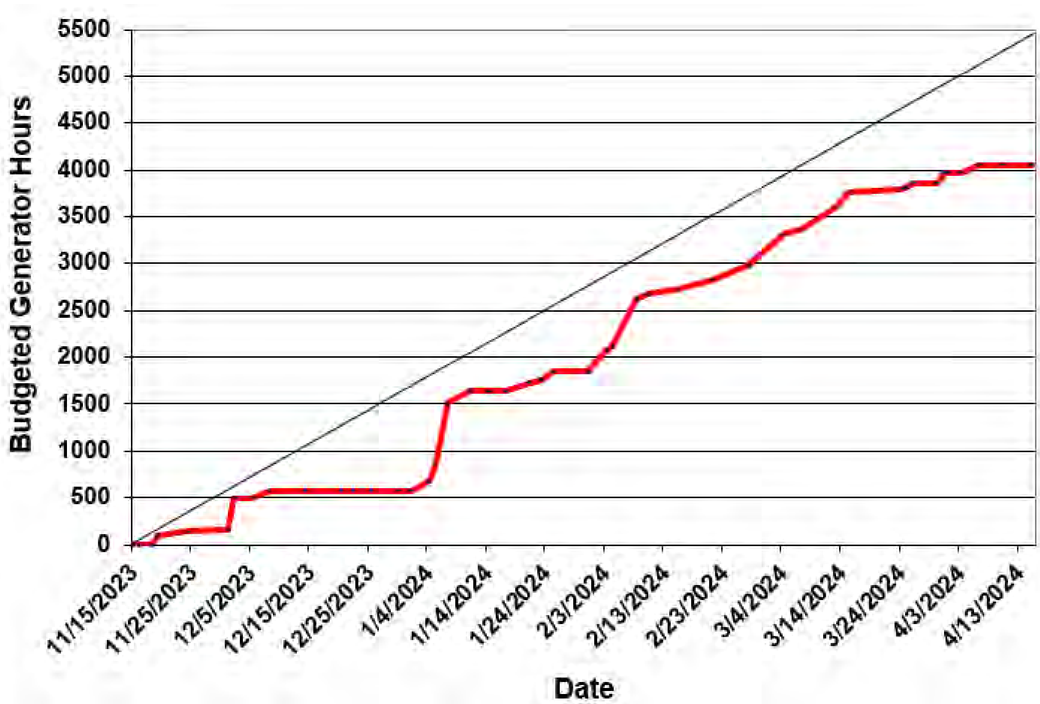


Figure 4.1. **Cumulative and budgeted seeding hours for the southern/central Utah core program and core program extension during the 2023-24 season. Red line shows actual usage this season, while the black diagonal line depicts a linear usage of budgeted hours.**

Table 4-1
Storm dates and generator usage, 2023-2024 season

Storm No.	Date(s)	Number of CNG Sites	Number of Generator Hours		
			Primary Contract	Lower Basin Extension	Total Hours
1	November 19	14	101.50		101.50
2	November 23-24	3	39.25		39.25
3	December 1	3	18.50		18.50
4	December 2-3	21	335.50		335.50
5	December 8	10	85.50		85.50
6	January 3-4	6	100.00		100.00
7	January 5	27	184.25		184.25
8	January 6-7	41	648.50		648.50
9	January 10-11	12	111.50		111.50
10	January 13-14	1	14.00		14.00
11	January 20-21	4	90.50		90.50
12	January 22-23	2	27.00		27.00
13	January 25	9	86.75		86.75
14	February 1-3	19	236.00		236.00
15	February 3	7	35.25		35.25
16	February 6-8	19	505.00		505.00
17	February 9-10	4	59.00		59.00
18	February 15	6	43.00		43.00
19	February 20-21	17	107.50		107.50
20	February 26-27	15	150.75		150.75
21	March 3-4	20	330.25		330.25
22	March 7	8	47.75		47.75
23	March 12-13	30	253.75		253.75
24	March 15-16	7	157.25		157.25
25	March 24	5		33.75	33.75
26	March 25	4		20.00	20.00
27	March 26	7		42.00	42.00
28	March 30-31	6		113.50	113.50
29	April 6	9		76.00	76.00
Total Hours			**3768.25**	**285.25**	**4053.50**

As of April 16, 2024, SNOTEL observations were indicative of a busy season. All basins throughout the state were above median snowfall, and precipitation since October 1 was above mean values for all areas except Southwestern Utah. It is worth noting that snowpack (SWE) percentages were higher than water year precipitation percentages. The primary reason for this is that a larger 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 affecting the precipitation totals, leading to cumulative precipitation numbers biased toward the low side at some sites. The April 16 data are summarized in Table 4-2.

Table 4-2
Snowpack and Precipitation Percentages on April 16, 2024

River Basin	No. of Reporting Stations	Snow Water Percent of Median	Water Year Precipitation Percent of Average
Tooele County	4	130%	115%
Price - San Rafael	9	122%	117%
Beaver River	3	122%	106%
Upper Sevier River	18	138%	102%
Southwestern Utah	10	108%	90%

Figure 4.2 provides the percent of normal median values of April 16 snow water content for Utah. Figures 4.3 – 4.5 show October 1, 2023 – May 31, 2024 snow water equivalent and normal values for three SNOTEL sites within the program's target areas.

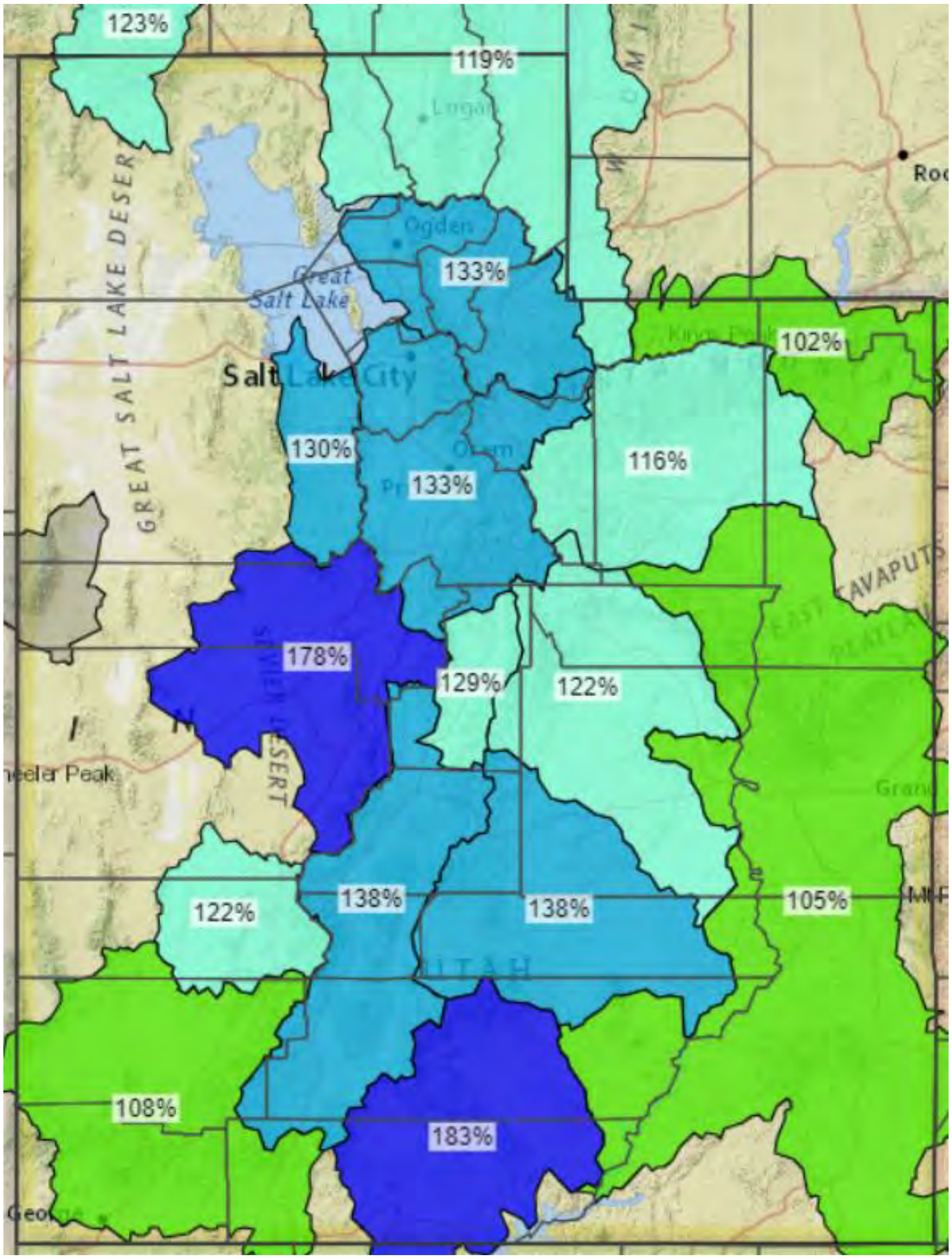


Figure 4.2. **Snow Water Equivalent Percent of Normal values in Utah on April 16, 2024.**

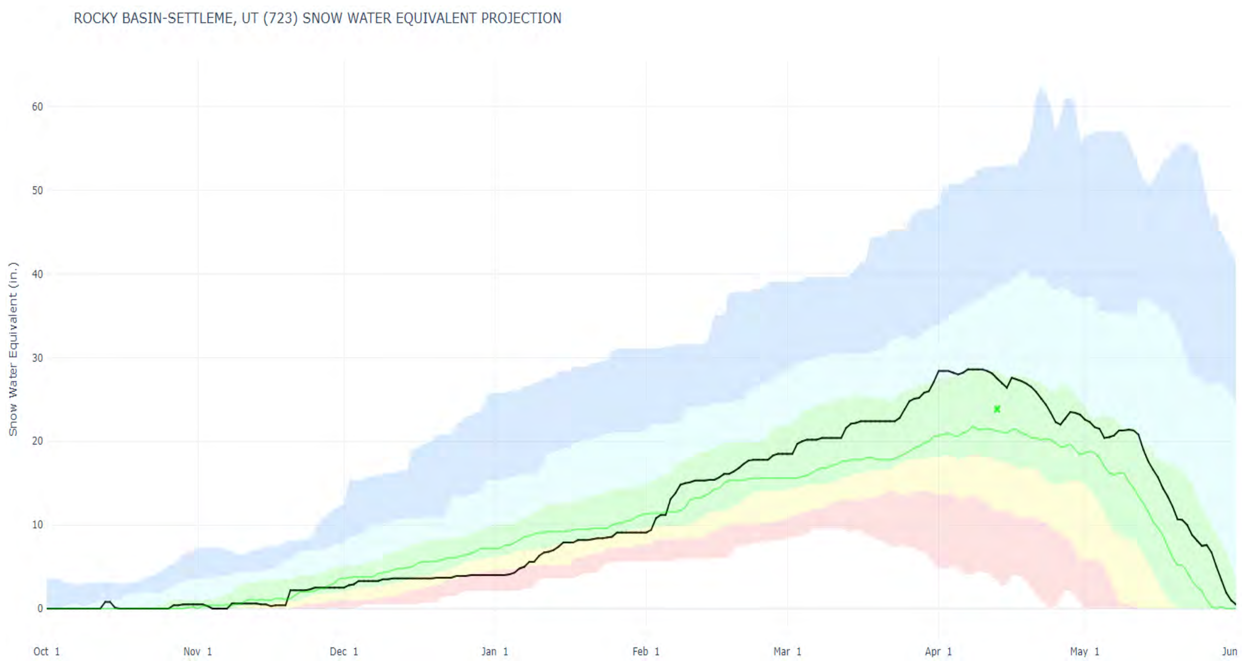


Figure 4.3. **NRCS SNOTEL snow water content plot for October 2023 through May 2024 for Rocky Basin-Settlement Tooele County. Black line is the 2023-24 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.**

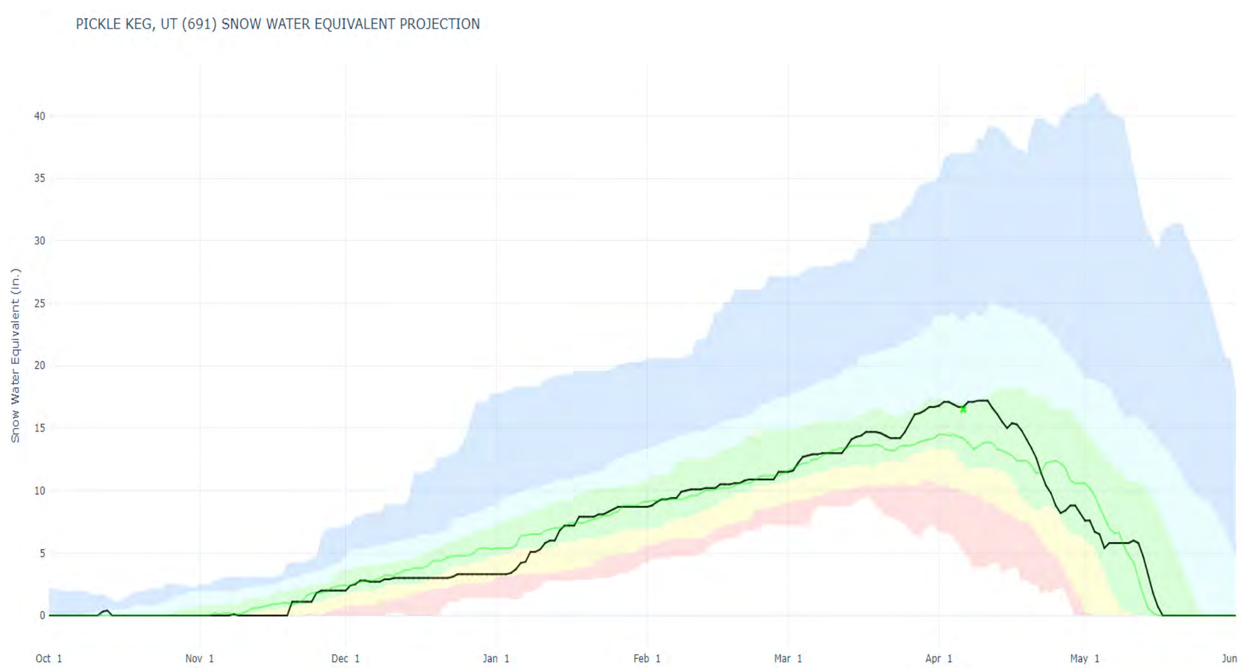


Figure 4.4. **NRCS SNOTEL snow water content plot for October 2023 through May 2024 for Pickle Keg in Central Utah. Black line is the 2023-24 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.**

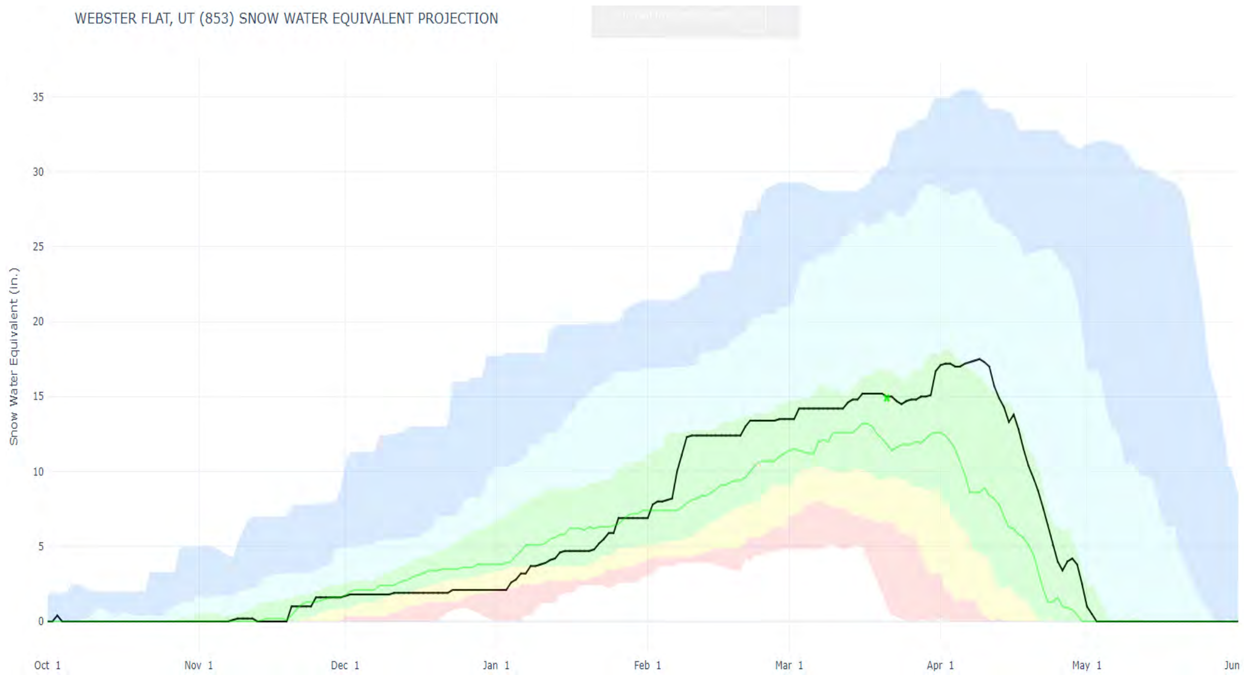


Figure 4.5. **NRCS SNOTEL snow water content plot for October 2023 through May 2024 for Webster Flat in southwestern Utah. Black line is the 2023-24 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.**

4.1 Operational Procedures

In operational practice, an approaching storm was monitored with the aid of continually updated online weather information. 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 2023

The weather pattern for November was fairly active, particularly during the second half of the month (beginning of the program seeding period) when three storm systems affected the area, two of which 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 16, a shortwave disturbance emanating from an upper low off the California coast pushed across Nevada and Utah accompanied by large-scale ascent and widespread precipitation. Temperatures aloft were warmer than ideal for seeding ops across the target area, with 700 mb temperatures of 0°C to +2°C as well as the presence of weak low-level stability. As such, no seeding operations took place.

On November 19, a trough of low pressure was approaching from the west with energy from a second trough diving southward through far western Canada merging into the former system. Precipitation arrived into western Utah ahead of the trough during the early morning hours, with thunderstorms across portions of west-central and southwest Utah during this time. As the trough pushed across the state, winds veered from westerly to north/northwesterly with a moist, unstable flow bringing rain and snow showers to the central and southern Utah mountains. Several sites were activated and ran from late morning into early evening before activity tapered off. SWE totals of 0.30”-1.50” were reported, with the highest amount of 2.00 inches at Little Grassy in southern Utah. High pressure moved into the area from November 20-22 with dry and mild weather, along with valley inversions in some locations.

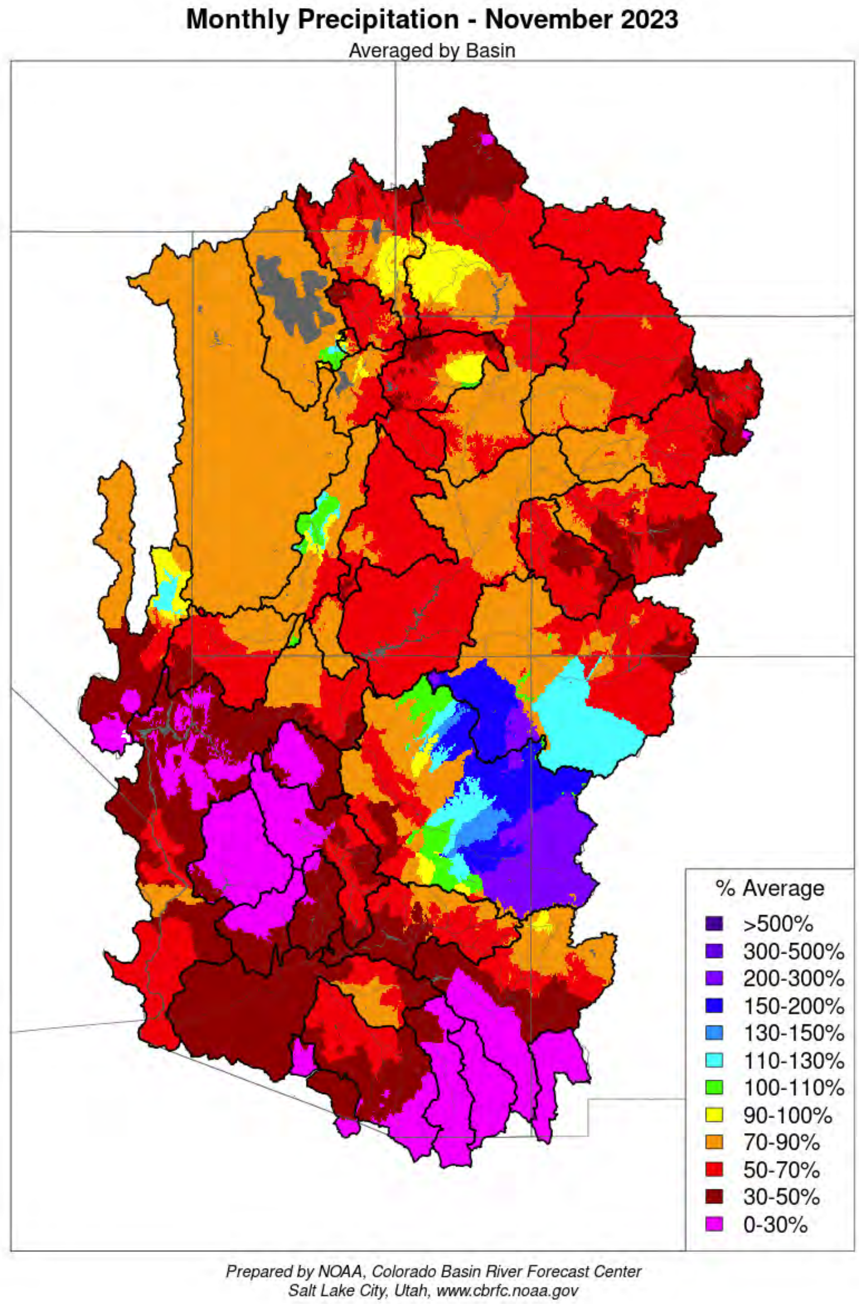


Figure 4.6. November 2023 precipitation, percent of normal.

On November 23, an upper level trough dropped into the Great Basin, and an upper level low developed across eastern Nevada/western Utah during the nighttime hours. Given the proximity of the low to the target area, winds were generally light. Temperatures at 700 mb were around -5°C with a rather dry sub-cloud layer. Over time, this layer became increasingly moist, and precipitation eventually began reaching the surface. On November 24, light and variable winds near the low continued, however some convective development occurring during the morning to afternoon period warranted activating a few sites across southwest Utah. As the low pushed east of the area, precipitation came to an end and seeding operations were halted. SWE totals for this event were low in and near areas where seeding occurred, generally less than 0.30”. After this event, a ridge of high pressure returned with increasing valley inversions and generally fair weather through November 29, with a weak trough developing over the area on November 30.

December 2023

December got off to an active start during the first week, with three storm events, two of which were tied to the same system. The remainder of the month was atypically quiet, save for a couple of minor precipitation events mainly across northern Utah in the week before Christmas. Figure 4.7 shows basin-averaged precipitation for the month.

A broad trough of low pressure was located across the Rockies/Intermountain West on December 1, with the trough axis sitting over Utah. 700 mb temperatures ranged from -10°C in northern Utah to around -7°C in the south. Winds were light, and some valley inversions were in place. Snow showers associated with a passing shortwave disturbance embedded in the trough moved across portions of southwestern Utah during the late morning and afternoon, with a few high elevation sites above the inversions during this period, shutting off by evening as the shortwave moved out of the area. SWE with this system ranged from 0.1-0.8”.

The next day, on December 2, the trough axis had moved further east, stretching from eastern Montana to the Texas Big Bend, with Utah under northwest flow aloft. Another shortwave disturbance embedded within the flow moved into Utah during the afternoon hours, first bringing snow and rain to northern Utah, then into central Utah by evening. 700 mb temperatures were around -11°C in the morning, warming to around -8°C by evening. A number of sites in Tooele County and into central Utah were activated during the evening and continued to run into December 3 as snow and low elevation rain continued, tapering off during the day. Temperatures aloft continued to warm, with 700 mb temperatures around -4°C by late afternoon. SWE totals with this second system were in the 0.1-1.2” range across the target areas.

High pressure moved over the area from December 4-6 with dry and mild weather across the state. A fast-moving cold front moved through Utah on December 7 with a quick shot of orographic snow showers over northern Utah. A second impulse that evening also brought more light snow to northern into central Utah, but with low SLW. Fair weather returned to the state on December 9 and remained through December 19 as high pressure influenced the weather during this period. A passing disturbance late in the evening of December 19 brought some light precipitation to northern Utah. Fair weather continued for central and southern Utah. On December 23 a trough of low pressure with associated cold front and band of precipitation moved across northern Utah, with precipitation along the Wasatch Front and western Uinta Mountains. Behind this system, dry and cold weather moved in with a northerly flow pattern in place that remained through Christmas Day. Warmer temperatures aloft moved in from December 26-29 with 700 mb temperatures rising to 0°C; with snow in many valleys and basins, inversions strengthened during this period. Clouds moved over the state on December 30 related to a dissipating trough of low pressure west of the area. The final day of 2023 was clear and cool with 700 mb temperatures falling to -4°C and valley inversions remaining.

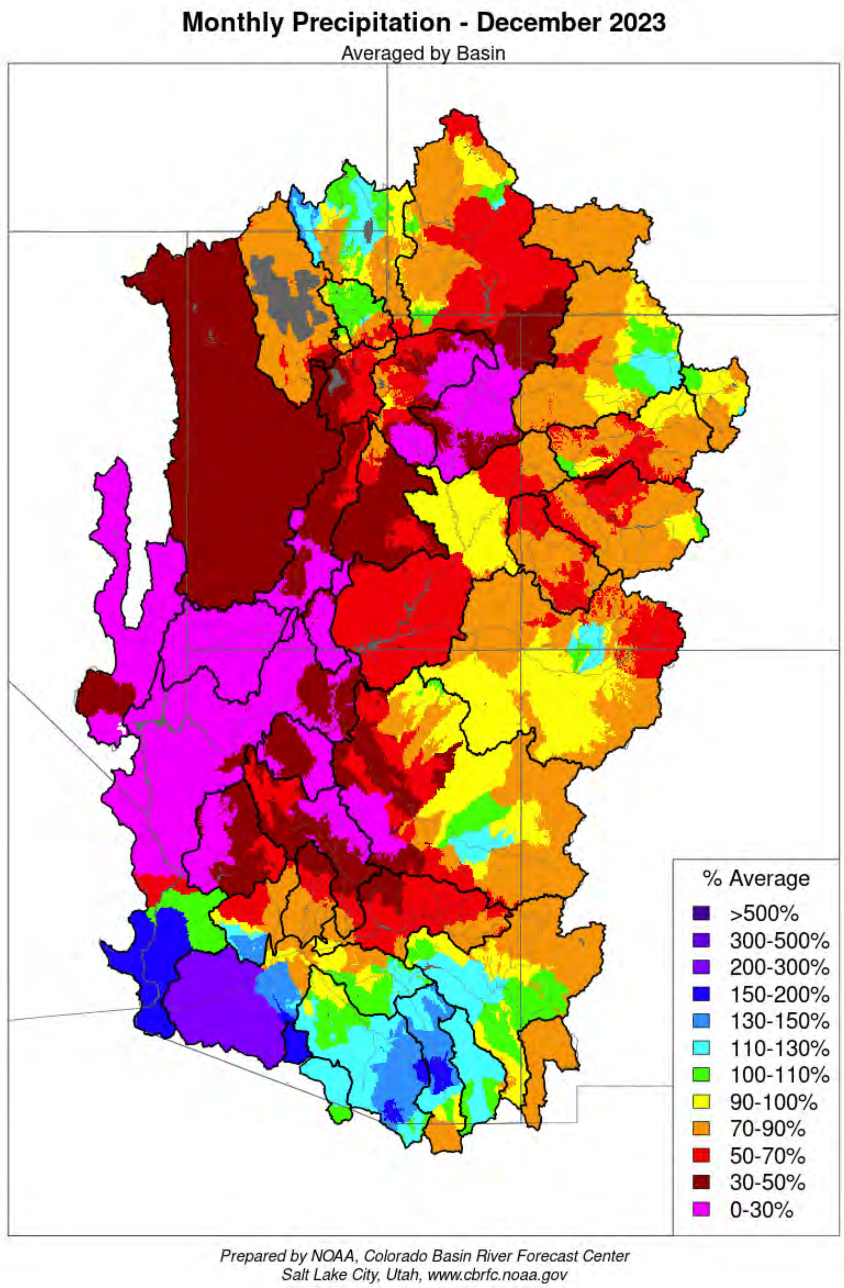


Figure 4.7. **December 2023 precipitation, percent of normal.**

January 2024

January 2024 turned out to be an active month weather-wise, with 9 storm events affecting central and southern Utah; eight of these saw seeding operations take place. These storm events were fairly evenly distributed across the month. Figure 4.8 shows the basin-wide averaged precipitation for Utah for January 2024, with near to above normal precipitation across much of the state, and below normal precipitation across portions of southern and especially eastern Utah.

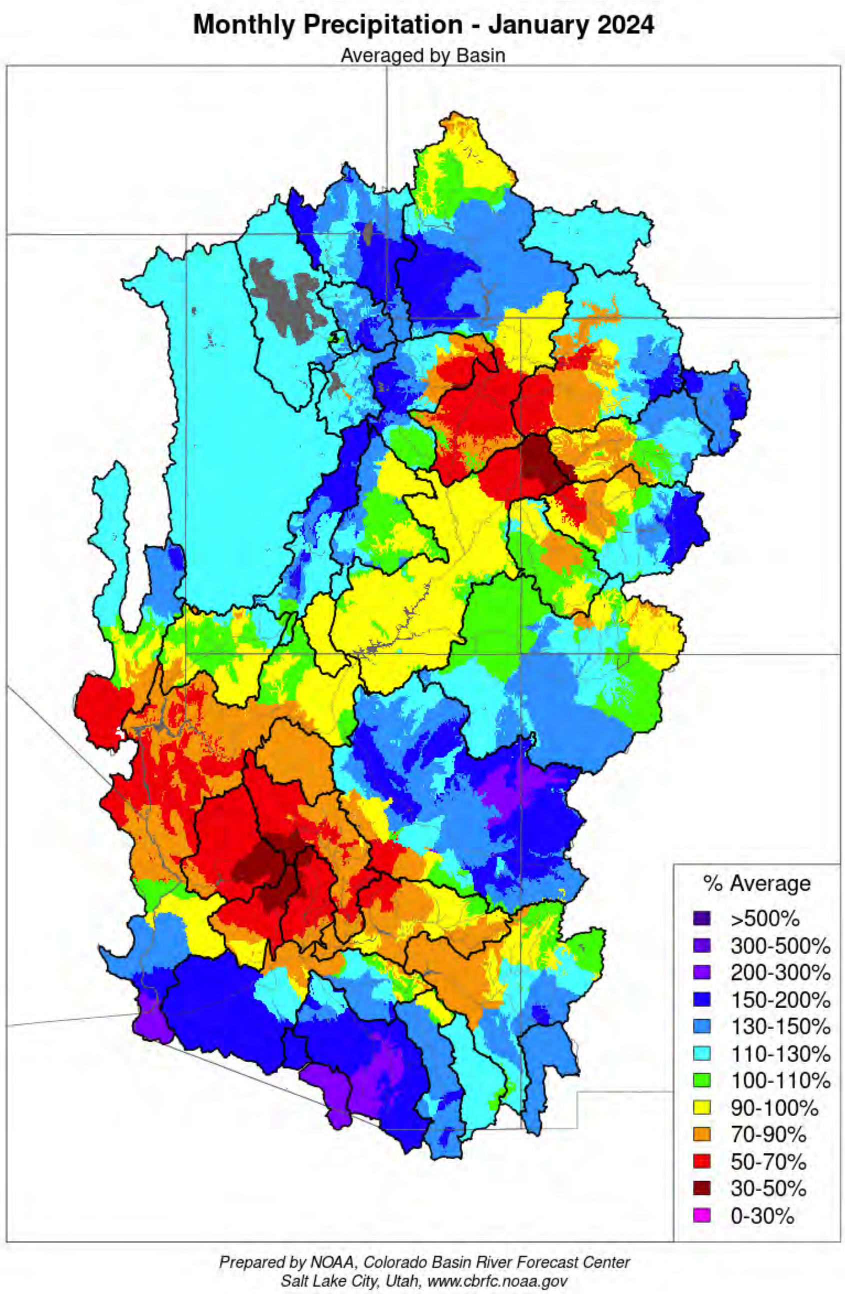


Figure 4.8. January 2024 precipitation, percent of normal.

The month began with a weak ridge of high pressure over the state on January 1-2 bringing dry and mild weather to the state, although valley inversions remained in many spots during this time. A deep trough of low pressure off the California coast moved inland on the night of January 2 and pushed into Nevada on January 3, with a closed circulation developing near Las Vegas. Southerly flow brought moisture into southwest Utah during the day and helped to mix out some of the low level inversions. Diffluent flow aloft also moved into southwest Utah, with precipitation increasing across this area. Several mid and high elevation sites across southwest Utah were activated during the afternoon and continued to run through the night into the morning of January 4 as the closed low passed to the south of St. George. Northerly flow moved in behind the low with precipitation tapering off. SWE totals from this event ranged from 0.2-0.9”.

On January 5, a shortwave trough over northern Nevada/southern Idaho moved southeast into northern Utah late in the morning and then across the rest of the state during the afternoon. 700 mb temperatures were around -12°C at SLC on the morning sounding with northwest flow in place. Precipitation spread from northwest to southeast across northern and central Utah, with a number of sites activated from Tooele County down to Sevier County during the event. SLW, although present, was not abundant per model output and occasional PIREP of rime icing. Precipitation tapered off during the evening with sites shutting down as a result. SWE totals with this event ranged from 0.30” to 0.80”. The next day, on January 6, another trough of low pressure was digging across California and Nevada aided by a jet streak diving southeastward on the backside of the trough. This setup placed Utah under deep southwest flow with some moisture flowing into the state. By evening, 700 mb temperatures were around -8°C and were expected to continue to cool overnight as moisture continued to flow into the state, however model guidance was suggesting low amounts of SLW. Still, many sites in central and southern Utah were activated in the evening and continued to run overnight as mainly light precipitation continued with winds becoming westerly. Tooele County sites were activated on the morning of January 7 as a cold front crossed that area with a band of enhanced snowfall accompanying it, followed by unstable northwest flow behind the front. The front continued to push across the rest of the state with winds turning northwesterly areawide. Temperatures continued to cool, with 700 mb temperatures of -12°C early in the morning, falling further to -15°C. By midday on January 7, sites were getting shut down as moisture appeared to be rather low. SWE amounts from this storm event ranged from 0.30” to 0.80”. A weak ridge of high pressure moved in for January 8, with cold mid-level temperatures (-16°C at 700 mb) and generally clear skies.

On January 9, a fast-moving shortwave disturbance with an accompanying cold front pushed through northern Utah bringing a round of moderate to heavy snow. Winds accompanying the front were strong with winds just off the surface reaching 50 knots, and as such sites in Tooele County were not activated due to the strong winds. The next day, another disturbance with accompanying cold front pushed across the state with moderate to heavy snow along and just behind the front, with lighter snow extending further behind the front along with much colder mid-level temperatures of -15°C. This crossed central Utah during the afternoon and evening hours, pushing into southern Utah for the nighttime hours; a number of sites were activated for the event, which ended early on the morning of January 10. SWE totals up to 1.30” in the central Utah mountains were recorded.

A very cold airmass was in place over Utah on January 11 with 700 mb temperatures of -18°C. Some snow showers were present across the north with very little SLW present. Additional weak impulses passed across Utah on January 12 and 13 while winds at low and mid-levels were rather strong, in the 30-50 kt range. Increasing low-level stability was observed on January 13, however one of the Brian Head sites above this stable layer was activated on the evening of January 13 as some snow moved across southwest Utah. Seeding ended on the morning of January 14 as precipitation tapered off. Of note, high and extreme avalanche danger existed during this time period across all Utah mountains.

Dry northwest flow was in place across Utah on January 15-16. A shortwave moved across the state on the evening of January 16 into the morning of January 17 accompanied by a wave of rain and snow. Per area soundings and observations, much of the area remained stable at low levels with this system and thus no ground seeding operations took place with this system. Northwest flow brought additional snow showers across northern Utah, but stability issues prevented operations for Tooele County. Quiet weather was observed on January 18-19 with warmer 700 mb temperatures of -4°C.

A broad trough was moving into the western U.S. on January 20 with a series of shortwave disturbances embedded within the trough poised to move across Utah. The first of these moved across the state during the day with rain and snow showers, however stability was present at low levels and the sub-cloud layer was initially rather dry; additionally, 700 mb temperatures were around -2°C. As precipitation continued to moisten the sub-cloud layer, eventually ground sites were reporting precipitation, however low level stability remained in some areas. Several high-elevation sites in southwest Utah were activated during the afternoon of January 20 and continued to run overnight into January 21 with precipitation becoming much lighter during the day; these sites were shut down by the afternoon hours. SWE totals of 0.10” to 0.50” were recorded.

A system passing through northern Arizona on January 22 brought increased moisture to portions of southwest Utah with south to southwest flow. A couple of sites in Washington County that were above the low level northeasterly flow and would target the Pine Valley Mountains were activated during the evening and ran into the morning of January 23. 700 mb temperatures were -4°C with PWAT values of around 0.40”. SWE totals of 0.20” to 0.70” were recorded around the mountains in Washington County.

On January 25, a shortwave trough moved into Utah from the west with rain and higher elevation snow accompanying it. Sites in southwest Utah were activated in the morning despite low level winds being rather light. 700 mb temperatures were around -3°C/-4°C across southern Utah with PWAT values around 0.40”. Scattered convection developed in the afternoon across southwest Utah and continued into early evening before ending, at which time ground sites were shut down. SWE totals of 0.20” to 0.60” were recorded. The remainder of the month saw high pressure over the area with warming temperatures and weak inversions in place for area valleys.

February 2024

The active weather pattern that took place in January continued into February 2024. Ten 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 Utah and elsewhere in the CBRFC forecast area.

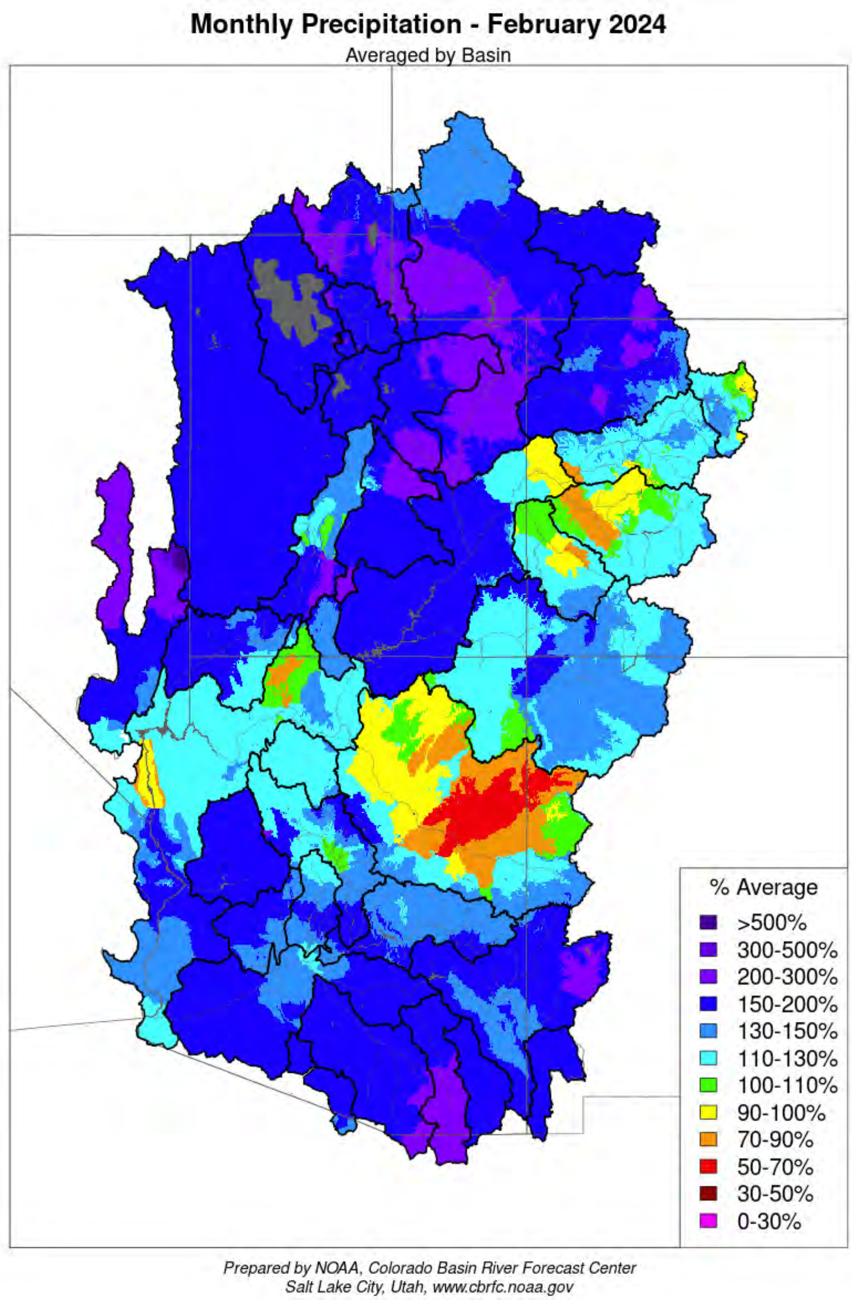


Figure 4.9. February 2024 precipitation, percent of normal.

A trough of low pressure approaching the West Coast on February 1 was forecast to split, with one piece moving across southern Nevada/southern Utah during the nighttime hours into February 2. Initially conditions were too warm and stable for ground seeding although there was more than sufficient moisture in place, and scattered thunderstorms were ongoing across mainly Washington County during the afternoon of February 1; Brian Head, above the stable layer, was activated during the afternoon. Deep southerly flow continued into February 2, but colder air moved in during the afternoon with winds becoming west to northwest and more unstable conditions developing. A number of sites were activated in southwest and central Utah as the convective activity developed and moved across the target areas. Precipitation tapered off across the southwest by evening and sites there were turned off, but sites in central Utah continued into the morning of February 3 as orographic snow showers continued across those areas. SWE amounts of 0.20-0.60" were common across the central and southwest mountains, with max totals up to 1.60" likely influenced by the heavier thunder(snow)storms across the southwest. Later in the day on February 3, moist unstable northwest flow aided in orographic snow showers developing across some areas. A few sites in Tooele County and also around the Pine Valley Mountains in southwest Utah were activated during the afternoon hours, ending by evening as activity waned with loss of heating. Additional SWE amounts of 0.10-0.40" were recorded.

A subtropical moisture plume associated with an atmospheric river moved into Utah on February 5 bringing precipitation to northern Utah. Temperatures aloft were rather mild, and no seeding efforts were made in Tooele County. The next day, February 6, additional moisture related to this weakening atmospheric river moved into southwestern Utah, and several sites were activated in these areas within southerly flow and where 700 mb temperatures were around -2°C. One caveat to the seeding operations at this point, winds were rather strong with the Cedar City radar VAD indicating southerly winds to 50+ knots so places like Brian Head were experiencing near blizzard conditions; seeding in such strong winds may have made targeting rather difficult. On February 7, as winds began to veer in central Utah, sites targeting the Manti-Skyline range were activated with model data suggesting heavier snow in this area. Precipitation continued across southwest and central Utah through the night of February 7, tapering off somewhat early on February 8, but additional orographic snow showers in northwest flow developed across portions of the state, so seeding operations continued, with a few Tooele County sites activated during the afternoon hours, ending by evening as activity came to an end. SWE totals for this event averaged 0.30-1.50" across the state, but several locations saw SWE totals over 2 inches, with a max of 4.60" in the central mountains and 5.40" in the far southwest part of the state. The next day, on February 9, precipitation moved across northern and central Utah associated with a shortwave disturbance. Seeding sites were contacted in Tooele County (although site operators were generally unavailable that day) and also in central Utah as rain and snow showers moved across those areas during the afternoon and evening hours, ending overnight. SWE amounts were low, generally under 0.25". February 10-14 was quiet weatherwise.

A shortwave disturbance moved across northern and central Utah during the day on February 15. Moisture was somewhat limited and initially the sub-cloud layer was rather dry, but as rain/snow showers began to develop within the upslope flow, this layer eventually moistened up. 700 mb temperatures were ideal, around -5°C to -8°C. Sites targeting the Manti-Skyline ridge were activated during the morning and continued into the afternoon, shutting off by evening as activity waned. SWE totals of 0.10-0.30” were reported. Additional precipitation developed/moved across portions of northern Utah on February 16 but did not affect the target area. Dry weather was observed on February 17. A weak trough crossed northern Utah on February 18 with some light snow and snow showers.

On February 20, a moist southwesterly flow was in place across Utah. Temperatures were mild across the state, with only a few of the high elevation sites below freezing. Precipitation had developed across portions of southwest Utah during the morning and continued through the afternoon hours. A couple of high elevation sites were turned on in southwest Utah during the afternoon and remained on through the night as precipitation continued across the area while temperatures remained on the mild side. Precipitation tapered off temporarily on the morning of February 21, and the high elevation sites were shut off. Later in the day, moist unstable westerly flow lifting over the mountains sparked extensive convective development, and a number of sites were activated from north-central through southern Utah, running until early evening when activity came to an end. SWE totals of 0.30-1.80” were reported, highest in the southwest. Dry weather occurred from February 22-25.

On February 26, a shortwave disturbance moved from the Pacific Northwest into Utah. A strong cold front accompanied the shortwave and moved across the state during the evening and overnight hours. A band of moderate to heavy snow formed along and just behind the front as it moved from northern through southern Utah. Strong wind gusts also accompanied the band of precipitation. Sites from Tooele County down to Sevier County were activated in the evening, running overnight as the band pushed through and shutting off on the morning of February 27 as it departed the state. SWE totals of 0.10-0.80” were reported, with a maximum of 1.00” in the central Utah mountains. The remainder of the month was relatively quiet.

March 2024

March 2024 continued the active weather pattern that began in January. A total of eight seeded storm periods were realized during the month. Figure 4.10 shows the basin-averaged precipitation across the CBRFC area. Above normal precipitation was observed at most locations in Utah; the exception was across southwestern Utah where 50-100% of the normal March precipitation was recorded.

On March 1-2, a deep trough was located west of Utah. Strong south to southwest flow was in place across Utah, with Wind Advisories and High Wind Warnings hoisted for much of the state as sustained winds of 25-40 mph with gusts to 60-70 mph were expected and verified as the event unfolded. A strong cold front pushed across the state on March 2 with rain, snow and thunderstorms along and behind the front as it moved through. Seeding did not take place due to the strong winds. On March 3, as the trough moved over Utah, temperatures aloft cooled significantly, with 700 mb temperatures of -11°C to -13°C. Although SLW was not plentiful, precipitation was in place across central and southern Utah and a number of sites were activated from Juab to Sevier counties from the afternoon of March 3 into the morning hours of March 4, when precipitation ended in those areas. SWE totals from this event ranged from 0.20” to 1.5”, highest in central Utah. Occasional very light precipitation occurred mainly over northern Utah on March 5-6, but no seeding operations occurred.

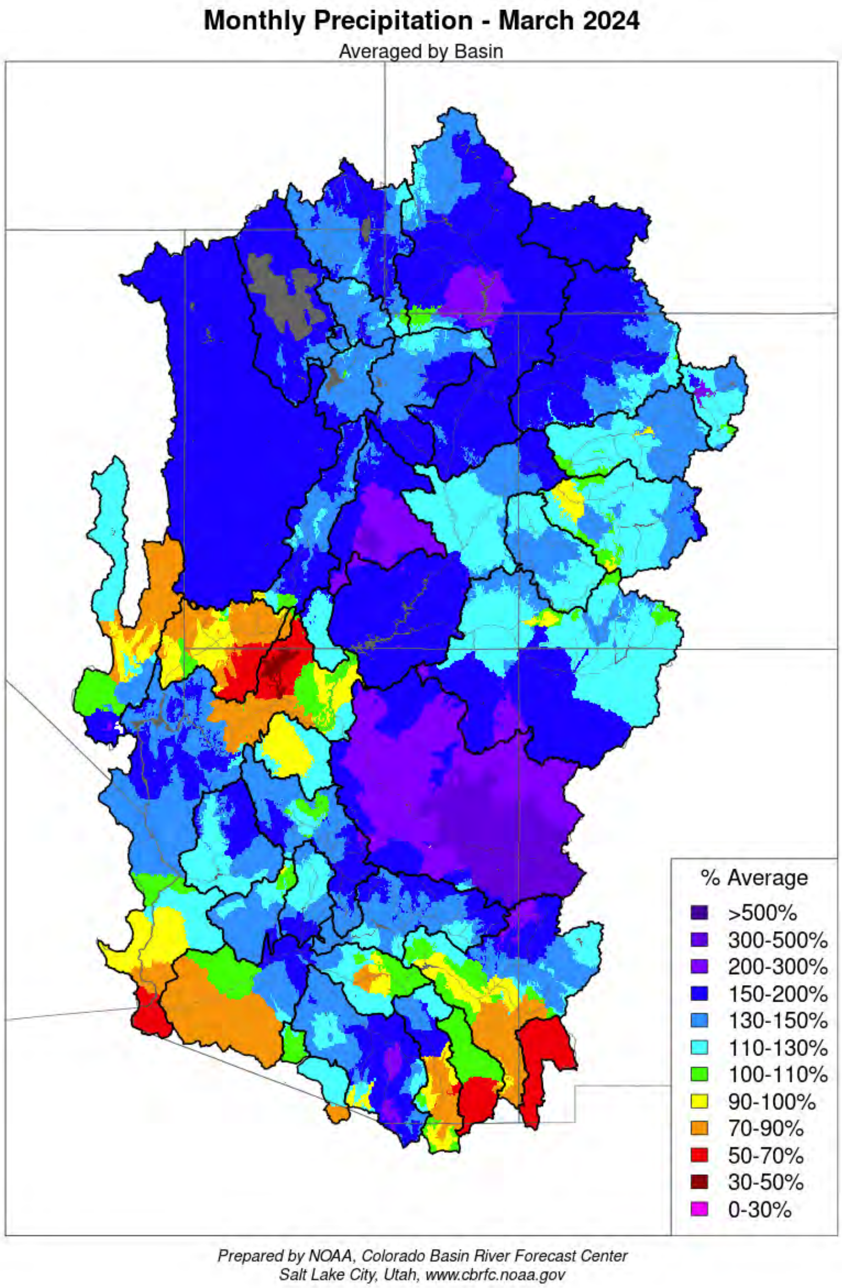


Figure 4.10. March 2024 precipitation, percent of normal.

A longwave trough was located over the western U.S. on March 7, with a low near the base of the trough moving across the Desert Southwest. Morning soundings showed PWAT values of 0.30-0.45" and 700 mb temperatures of -4°C to -7°C. With daytime heating, scattered to numerous rain/snow showers and isolated thunderstorms developed across the southwest quadrant of Utah, and several sites from southern Millard County to near Zion NP were activated during the afternoon hours as this activity moved south and southeast across the area, ending during the evening. SWE totals of 0.25” or less were recorded. Dry and quiet weather occurred from March 8-11.

On March 12, a trough of low pressure located over the Pacific Northwest was expected to dive southeast toward Utah accompanied by a strong cold front. The front entered northwestern Utah during the afternoon hours and would slice through the state during the afternoon and nighttime hours. Strong lift accompanying the front helped to develop a band of rain, snow and thunderstorms along and just behind the front. Sites in Tooele County were activated during the afternoon just ahead of the arrival of the front, shutting off by evening as precipitation ended there. For central and portions of southern Utah, sites were activated in the evening ahead of frontal passage, and sites across central Utah were shut off prior to midnight, with sites in southern Utah shutting off early on the morning of March 13 as the front cleared the state. SWE totals of 0.10-0.60” were reported.

An upper low was wobbling around the Lower Colorado River Valley in California/Arizona on March 15-16. This positioning placed southern Utah under east to southeast flow. PWAT values of 0.40-0.55” were in place, with 700 mb temperatures of -4°C to -8°C. Some sites in southern and southwestern Utah were activated during the late morning/early afternoon of March 15 and continued to run into the morning of March 16 as moisture continued to stream into the area on the north side of the low. SWE totals with this storm event ranged from 0.20” to as high as 2.60” in the Escalante Mountains, where moist orographic lift from the southeast flow was maximized. From March 17-22, dry and mild weather kept operations quiet. Although the March 15-16 event marked the end of the core program period, storm events that followed during the remainder of the season were seeded for the Lower Basin extension areas which remained active.

A strong cold front moved across northern Utah in the late afternoon to evening hours on March 23. 700 mb temperatures were around 0°C ahead of the front. Initially, the sub-cloud layer was quite dry, even with the radar showing abundant echoes of moisture. As precipitation continued to fall through this layer, eventually rain and snow with embedded thunderstorms began to reach the surface but by then precipitation began to taper off. The following day, on March 24, moist, unstable northwest flow developed. With daytime heating, scattered convection developed across the western half of Utah. Some sites in southwest Utah were activated just after noon and continued into the evening as these hit-and-miss rain/snow showers and isolated thunderstorms moved southeastward, ending during the evening hours. SWE totals on March 24 were generally under 0.50”. A broad trough remained across the western U.S. on March 25, and a subtle shortwave disturbance was moving southeast across the state. With daytime heating, scattered convective cells once again developed across portions of the state. Some sites in central Utah were activated with seeding sites running until evening when all activity diminished. Snowfall amounts of 1-4” were recorded, with SWE amounts generally under 0.10”. This process was replicated a third time on March 26, with the broad trough remaining over the western U.S. and yet another shortwave disturbance traveling southeastward across Utah. With ample moisture in place and 700 mb temperatures -6°C to -9°C, scattered convective cells developed by midday and continued into the evening hours before ending. Given the difficult targeting with the randomness of the convection, several sites were activated across central and southern Utah in an attempt to target these random cells. SWE totals were similar to the previous day, generally less than 0.10”.

One final storm event moved across Utah in March. An upper low was dropping southward off the central California coast on March 30. This feature was at the base of a positively tilted trough that stretched from the low northeastward across the Great Basin and northern Rockies into southern Canada. This placement resulted in south to southwest flow across Utah, with diffluent flow aloft over southwestern Utah which was helping to increase lift across this area. Initially 700 mb temperatures were on the warm side, around -2°C over southern Utah, but as the low/trough gradually moved closer to Utah, temperatures cooled by a few more degrees. Moisture was adequate, with PWAT values 0.40-0.50” across the area. Precipitation began in the morning across southwest Utah, and a few high elevation sites were activated. As the area of precipitation increased across southwest Utah in the afternoon, a couple more sites were added. Precipitation continued through the evening and overnight, tapering off during the morning of March 31. All sites were subsequently shut off between 0900 and 1000. SWE totals for this last event in March were generally between 0.20” and 1.00”, with maximum totals of 1.50-2.50” across the southwestern Utah mountains.

April 2024

In a pattern that closely mimicked last winter’s weather, April turned out to be a relatively quiet month, with one storm event early in the month. Precipitation totals were below average, as indicated in Figure 4.11.

The one storm event before the end of the program took place on April 5-6. A deep trough was located over the West Coast states on April 5 with strong southerly flow across Utah along with mild temperatures (0°C at 700 mb). A north to south band of moisture slowly advanced eastward across the state along a cold front. No seeding of this took place due to the warm temperatures and the southerly winds. As the trough slid into Utah on April 6, temperatures dropped significantly to -11°C at 700 mb and winds turned westerly and northwesterly. Scattered snow showers developed early in the morning with the greatest focus on the central Utah mountains. Several sites across Sanpete and Sevier counties were activated, running from mid-morning until early evening when activity tapered off. SWE totals from this final storm of the season were in the 0.10-0.30” range. Dry weather finished the last week and a half of the season.

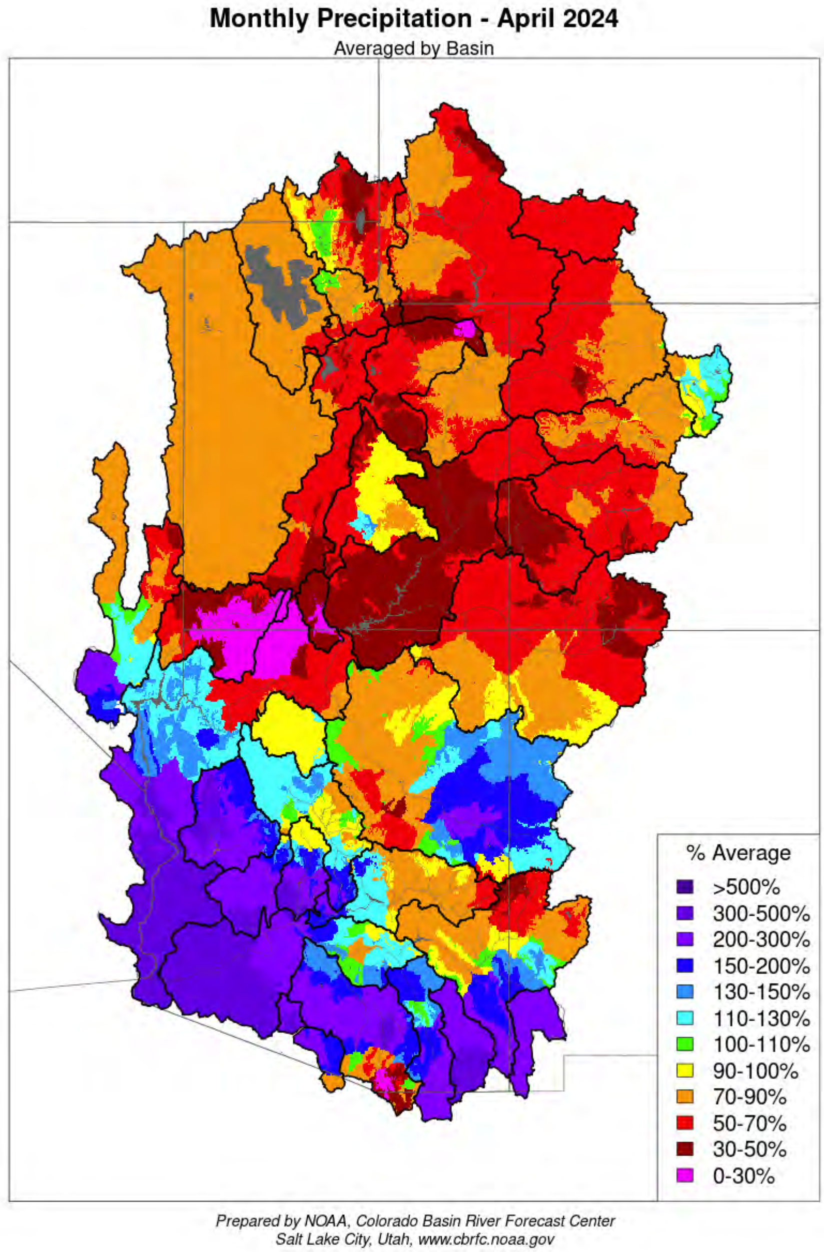


Figure 4.11. April 2024 precipitation, percent of normal.

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 the target areas have been evaluated to assess the efficacy of cloud seeding, by examining the precipitation observed at the gauges within the two seeded target areas. 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. As noted in the discussion of control sites for these analyses, NAWC elected to utilize a different evaluation technique this season for Utah ground-based programs. This is discussed further in section 5.6.

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 listed in Appendix C and 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 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 gauge 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. 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.

For the 2024 winter season, the State of Utah and local sponsors significantly expanded seeding into new areas in northern and central Utah. Some SNOTEL sites used as non-seeded "control" sites for the seasonal evaluations are now in areas targeted by seeding operations; for the Southern and Central Utah program, this affected the Eastern Tooele County target area analysis, while other seeding programs further north have seen more of their control sites become situated in newer target areas. For this reason, and given the number of years already in the seeded set, it was determined that instead of updating the precipitation and snowpack evaluation on an annual basis, the previously obtained long-term results of these evaluations would be used in combination with an additional approach to derive estimates of streamflow increases using target/control results. This approach was applied to the Southern and Central Utah program (Primary Target Area) as well as others around the state, even though the expanded seeding operations affected the various northern Utah target/control evaluations more directly.

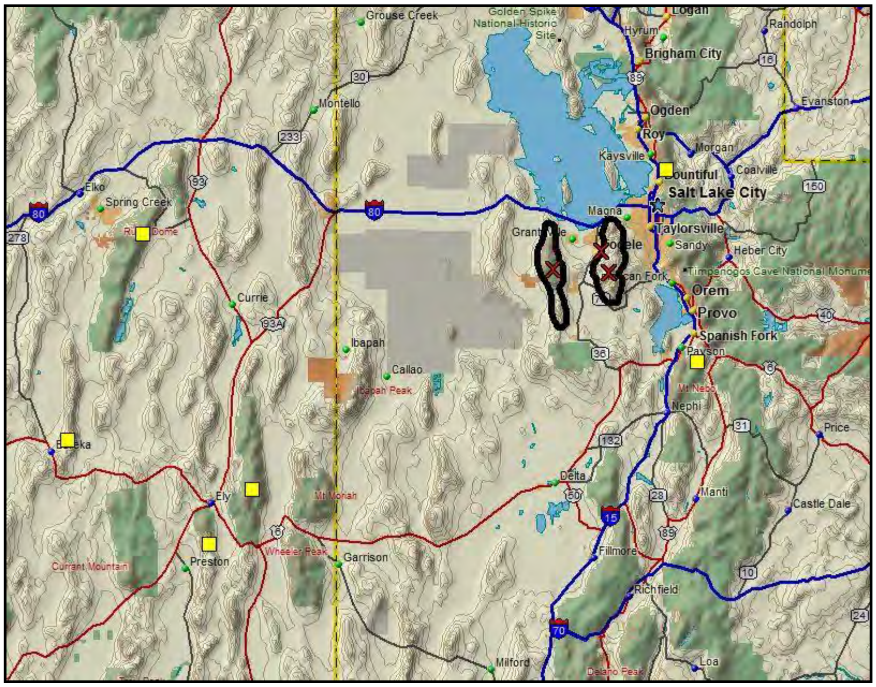


Figure 5.1. **Precipitation sites for Eastern Tooele target/control evaluation; control sites are depicted as squares and target sites with an X.**

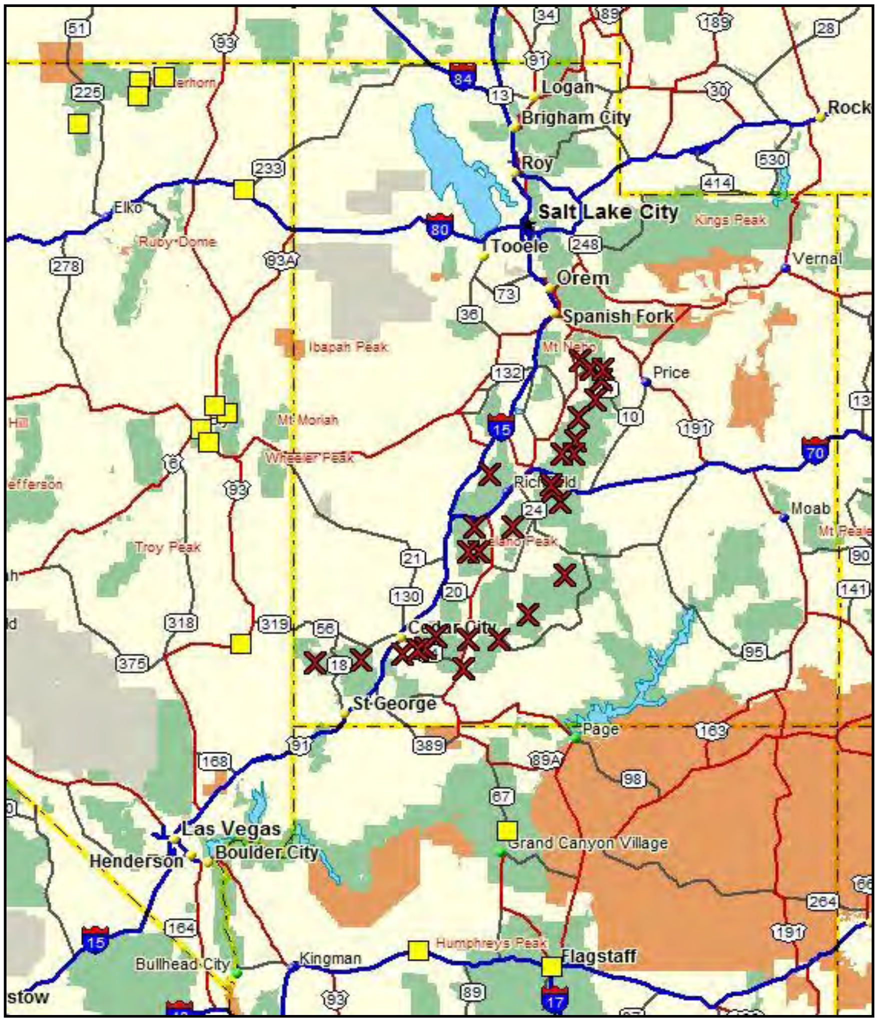


Figure 5.2. **Precipitation target (X) and control (square) sites, primary target area.**

5.3.3 Precipitation Linear Regression Results

For Eastern Tooele County, the target/control data combined for the 39 seeded December-March periods (beginning in 1976 but excluding WY 1982-1988 and 1993-1995), the indicated average increase in the target area is 13%. The seasonal (December-March) difference between the observed and calculated precipitation is an area-wide average of 1.5 inches more than predicted during the seeded periods.

For the Primary Target area, the target/control data combined for the 46 seeded December-March periods (beginning in 1974 but excluding WY 1984-1988), the indicated average increase in the target area is 11%. The seasonal (December-March) difference between the observed and calculated precipitation is an area-wide average of 1.2 inches more than predicted during the seeded periods.

5.4 Snow Water Equivalent (SWE) Evaluations

Snowpack data (SNOTEL and snow course) have been used in the past to evaluate both portions of the Southern and Central Utah seeding program.

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. 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 is approximately 8,050 feet MSL.

The Primary Target control group consists of ten SNOTEL/snow course sites located from southern Idaho southward through eastern Nevada into north-central Arizona. 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.

As described in section 5.3.2, for the Utah ground-based seeding programs a different evaluation approach was employed this season given the large set of seeded-season data that has yielded a long-term estimate of seeding increases to precipitation and snow in this area.

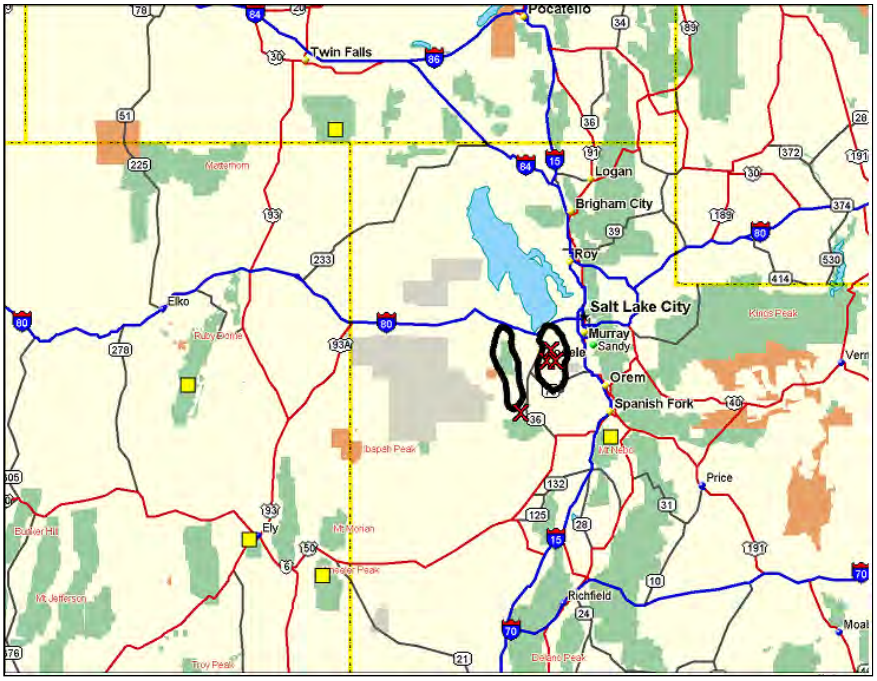


Figure 5.5. **SWE sites for Eastern Tooele target/control evaluation (squares are control sites, X's are target sites).**

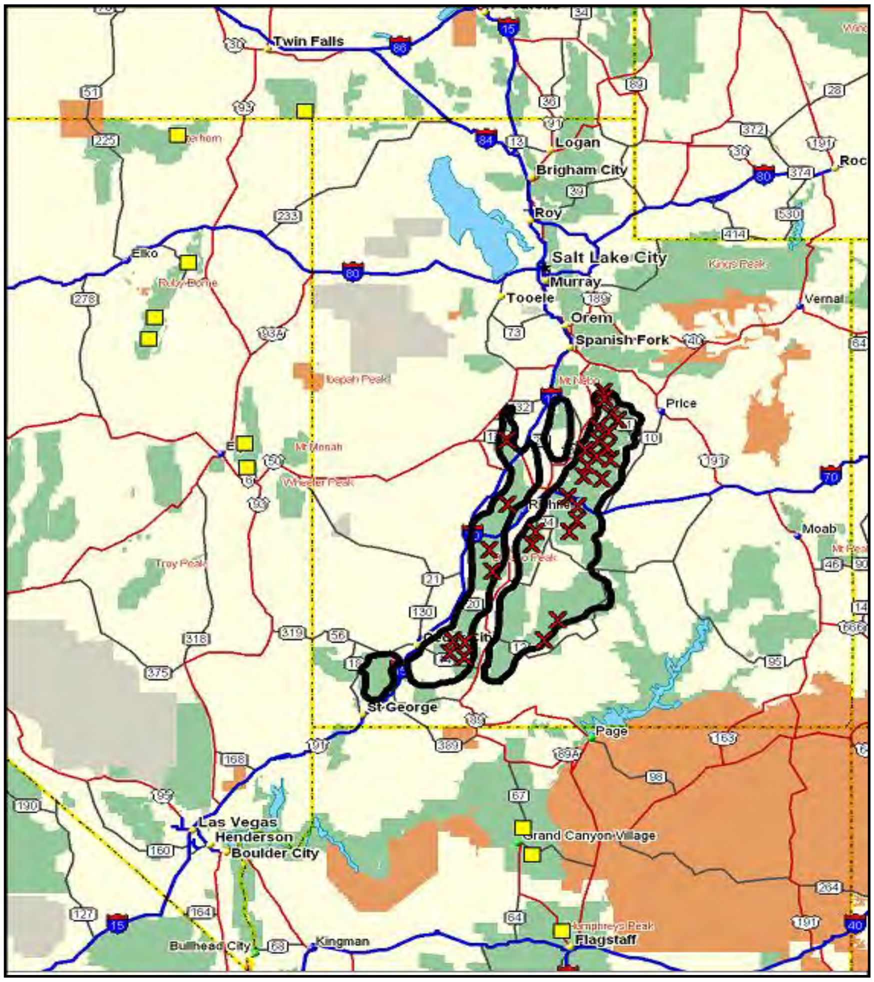


Figure 5.6. **SWE sites for Primary Target evaluation (squares are control sites, X's are target sites)**

5.4.3 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 5-1. 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.

Table 5-1
Snow water content evaluation results for all seeded seasons

Target Group	Seeded Period	Ratio (observed/predicted)	SWE Increase (observed-predicted)
Eastern Tooele (ETT)	35 water years*	1.10	1.3
Primary Target (PT)	42 water years*	1.04	0.5

*** 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.

5.5 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 5-2
Summary of ratios from precipitation and SWE evaluations

Target Area Evaluation	Long-term Average	Excess Water (inches)
ETT Precipitation Linear	1.13	1.5
ETT SWE Linear	1.10	1.3
PT Precipitation Linear	1.11	1.2
PT SWE Linear	1.04	0.5

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 combinations 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. Additional streamflow analysis is discussed in the next section.

5.6 Determining the Impact of Cloud Seeding on Streamflow

Given the large number of seeded seasons that have been evaluated for this program (greater than the data set of historical, non-seeded seasons on which the regressions are based), NAWC elected to add some streamflow data evaluations to the mix of evaluations for this season's report instead of adding another season to the seeded evaluation set. For most of the Utah programs in general, this new approach was related to the fact that many sites previously utilized as control sites are now subject to effects of seeding operations, with the addition of remotely operated seeding sites during the past season. Adding new regressions of snowpack/precipitation vs. seasonal streamflow provides estimates of likely streamflow increases where well-correlated (e.g. natural, unregulated flow) gauge sites are available, utilizing previously obtained increase estimates to the precipitation and snow in the target areas.

5.6.1 Results – Impact of Cloud Seeding on Runoff

For the streamflow analyses, gauges on the Virgin River at Virgin, Sevier River at Hatch, Salina Creek near Emery and South Willow Creek near Grantsville were correlated to SNOTEL data in these respective watersheds. For streamflow, a seasonal period of March-July has been used in order to capture the bulk of the seasonal runoff without additional input from precipitation outside the winter season. This was found to be well-correlated to April 1 snow and seasonal (November-April) precipitation. The streamflow versus snowpack and precipitation relationships are essentially independent of seeding effects, so both seeded and non-seeded years can be included in these regressions.

For the Virgin River at Virgin gauge, correlation to April 1 snowpack to Kolob (the best correlated SNOTEL site) produced an R value of 0.94 (R^2 = 0.88). Results suggest that a 5% increase in seasonal snowpack (due to seeding) would produce a 9.7% increase in runoff in the Virgin River for an average season. This higher percentage increase to runoff (compared to the seeding increase to snowpack) may seem counterintuitive but is actually an expected result of these analyses when dealing with percentages. This is due to the negative offset term in the equations, a consequence of the fact that there is some inefficiency in converting snowpack to streamflow and a certain amount of water will evaporate or be lost to other processes such as uptake by the soil and vegetation. Thus, increasing the total snowpack or seasonal precipitation by a given percentage will increase the actual runoff by a higher percentage, given that the runoff represents the excess after these other processes have occurred. Given an average base flow in the Virgin River of over 73,000 acre-feet (AF) during the seasonal period of March-July, this estimated seeding increase would amount to over 5300 AF in an average season. When correlating the Virgin River gauge with seasonal precipitation (again, from the Kolob SNOTEL), a 5% increase in seasonal precipitation would suggest an increase in streamflow of 11%, or about 6600 AF.

For the Sevier River at Hatch, correlation to April 1 snowpack to Midway Valley (the best correlated SNOTEL site) produced an R value of 0.93 (R^2 = 0.86). A 5% increase in April 1 snowpack results in a 12.8% increase in streamflow. Applied to an average season with a base seasonal flow of approximately 55,000 AF, this would amount to an additional 4330 AF of runoff. Using a 5% increase in seasonal precipitation at Midway Valley due to seeding, the estimated increase in runoff in the Sevier River would be 11.5% for an average season; with a base seasonal flow of roughly 55,000 AF, this would amount to an additional 5200 AF of runoff.

For the Salina Creek near Emery, correlation to April 1 snowpack at Pickle Keg produced an R value of 0.81 (R^2 = 0.66). A 5% increase in April 1 snowpack results in a little over 8% increase in streamflow. Applied to an average season with a base seasonal flow of approximately 8050 AF, this results in an additional 588 AF of runoff. Using a 5% increase in seasonal (Nov-Apr) precipitation, the estimated increase in runoff in the Salina Creek would be 11.6% for an average season; with a base seasonal flow of approximately 8050 AF, this would amount to an additional 811 AF of runoff.

For the South Willow Creek near Grantsville in Tooele County, correlation to April 1 snowpack to Mining Fork (the best, and only SNOTEL site) produced an R value of 0.81 (R^2 = 0.66). Results suggest that a 5% increase in seasonal snowpack as a result of seeding would produce a 5% increase in runoff in South Willow Creek for an average season. Applied to an average season with a base seasonal flow of approximately 3000 AF, this would amount to an approximate additional 150 AF of runoff due to seeding. The correlation of the South Willow Creek gauge to seasonal precipitation was lower, with an R value of 0.76 (R^2 = 0.57). Using seasonal precipitation, a 5% increase would result in an estimated runoff increase of 6.1%; with a base seasonal flow of nearly 3000 AF, this would amount to an additional 180 AF of runoff.

These streamflow data represent only a fraction of the runoff from the seeding target areas, of course. The suggested increases in seasonal (March – July) streamflow of roughly 5-13% could be scaled to the total runoff for the seeding target areas as a whole. In any case, a higher **percentage** increase to streamflow (than the seasonal percentage increase to precipitation/snowpack) is an expected result, as seen in these evaluation results that resulted in an estimated 5-13% streamflow increase from a (conservative) 5-6% average seasonal precipitation and snowpack increase due to seeding.

REFERENCES

Gabriel, K.R., 1999: Ratio statistics for randomized experiments in precipitation stimulation. *J. Appl. Meteor*., 38, 1546-1550.

Griffith, D.A. and M.E. Solak, 2000: Summary of 2000 water year operations and evaluation of a cloud seeding program in central and southern Utah. NAWC Report No. WM00-2 to Utah Water Resources Development Corporation and State of Utah, Division of Water Resources.

Griffith, D.A., and M. E. Solak, 2001: Summary of 2001 water year operations and evaluation of a cloud seeding program in central and southern Utah. NAWC Report No. WM01-2 to Utah Water Resources Development Corporation and State of Utah, Division of Water Resources.

Griffith, D.A., and M. E. Solak, 2002: Summary and Evaluation of 2001-2002 Winter Cloud Seeding Operations in Central and Southern Utah. NAWC Report No. WM02-2 to Utah Water Resources Development Corporation and State of Utah, Division of Water Resources.

Griffith, D.A., M.E. Solak and D.P. Yorty, 2009: 30+ Winter Seasons of Operational Cloud Seeding in Utah. WMA, *J. Wea. Modif*., Vol. 41, pp. 23-37.

Griffith, D.A., D.P. Yorty, M.E. Solak and T.W. Weston, 2010: Potential Streamflow Increases that may result from Increases in Precipitation due an Extension Period of Cloud Seeding Operations in Central and Southern Utah. North American Weather Consultants report to The Six Agency Committee, Central Arizona Water Conservation District and Southern Nevada Water Authority, 54 p.

Griffith, D.A., D.P. Yorty, W. Weston and M.E. Solak, 2013: Winter "Cloud Seeding Windows" and Potential Influences of Targeted Mountain Barriers. WMA, *J. Wea. Modif*., Vol. 45, pp. 44-58.

Hasenyager, C., S. McGettigan and D. Cole, 2012: Utah Cloud Seeding Program, Increased Runoff/Cost Analyses. Utah Department of Natural Resources, Division of Water Resources, 18 p.

Mason, D.J. and M. Chaara, 2007: Statistical Analysis of NAWC's Winter Cloud Seeding Program for Central and Southern Utah. Report on independent statistical analysis.

Risch, D. A., J. R. Thompson and D. A. Griffith, 1989: Summary of operations (1989 water year) and evaluation of a cloud seeding program in central and southern Utah. NAWC Report No. WM84-12 to Utah Water Resources Development Corp. and State of Utah, Div. of Water Resources, November 1989.

Solak, M. E., D.P. Yorty and D. A. Griffith, 2003: Estimations of Downwind Cloud Seeding Effects. Utah. *J. Wea. Modif*., Vol. 35, pp. 52-58.

Stauffer, N.E. and K. Williams, 2000: Utah Cloud Seeding Program, Increased Runoff/Cost Analyses. Utah Department of Natural Resources, Division of Water Resources, February 2000.

Silverman, B.A., 2007: On the use of ratio statistics for the evaluation of operational cloud seeding programs. *J. Wea. Modif*., Vol. 39, 50-60.

Thompson, J. R., D. A. Griffith and D. A. Risch, 1990: Summary of operations (1990 water year) and evaluation of a cloud seeding program in central and southern Utah. NAWC Report No. WM90-7, to the Utah Water Resources Development Corp. and State of Utah, Div. of Water Resources, November 1990.

Thompson, J. R., D. A. Griffith and D. A. Risch, 1994: Summary of operations (1994 water year) and evaluation of a cloud seeding program in central and southern Utah. TRC/NAWC Report No. WM94-4, to the Utah Water Resources Development Corp. and State of Utah, Div. of Water Resources, August 1994.

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, 2023-2024
Storms 1-9

Storm	1	2	3	4	5	6	7	8	9
Dates	Nov 19	Nov 23-24	Dec 1	Dec 2-3	Dec 8	Jan 3-4	Jan 5	Jan 6-7	Jan 10-11
SITES									
TO1							7	7.5	
TO2							6.75	7.25	
TO3									
TO4				18.25				7.25	
TO5				16.75			7.5	7.25	
TO6				17			7.5		
TO8							7.5	8.5	
TO9							8.75	7.5	
TO10							7.25		
TO11									
CU1									
CU2					8.75		6		
CU3					8.75		6	18	
CU4								19.75	
CU5	8.75			16.5			6	18	
CU6							7	18	5
CU7				16				18	4.5
CU9							6	19.25	3.5
CU10	6.5			14.75			7	17.75	
CU11	6.75								11.5
CU12				14.75				17.75	11
CU13								20	11
CU14				18.5	9		7	10.75	
CU15				17.5	8.75		7	18	
CU16				17.5	8.75		7		
CU17				19.5	7		7		
CU18				14	8.75		7	18	

Storm	1	2	3	4	5	6	7	8	9
Dates	Nov 19	Nov 23-24	Dec 1	Dec 2-3	Dec 8	Jan 3-4	Jan 5	Jan 6-7	Jan 10-11
SITES									
CU19				18.75	8.75		7	18	
CU20	9			18.75	8.5		7		12
CU21	8.75			18	8.5			18.5	
CU22	8.5			13.5			7	17.75	
CU23	8.75			14.5			7	19.5	
CU24				16			6	17.75	
CU25				15.5			6	19	11.5
CU26				5			6	17.5	11
CU27				14.5					11.5
CU28							6		
CU29							7	18	8
SU1	5.5							5.5	
SU2	5.5							16.25	
SU4									
SU5									
SU7	8.5	6.5						17.5	
SU9									
SU11	7	24.25	5.5			17.5		20.5	
SU12								17.5	11
SU14	5.5					16.5		17.25	
SU15						16.5			
SU19									
SU20	7.75							17.5	
SU21									
SU23	4.75	8.5	6.5			17		17.5	
SU24									
SU25			6.5			16.5		16.25	
SU27									
SU28						16		17.25	
SU29								11	
SU30								17.5	

Storm	1	2	3	4	5	6	7	8	9
Dates	**Nov 19**	**Nov 23-24**	**Dec 1**	**Dec 2-3**	**Dec 8**	**Jan 3-4**	**Jan 5**	**Jan 6-7**	**Jan 10-11**
SITES									
SU32								17.5	
SU33								17.5	
SU34								17.5	
Storm Total	**101.5**	**39.25**	**18.5**	**335.5**	**85.5**	**100.0**	**184.25**	**648.5**	**111.5**

Table B-2
Generator Hours – Central and Southern Utah, 2023-2024
Storms 10-18

Storm	10	11	12	13	14	15	16	17	18
Dates	Jan 13-14	Jan 20-21	Jan 22-23	Jan 25	Feb 1-3	Feb 3	Feb 6-8	Feb 9-10	Feb 15
SITES									
TO1									
TO2									
TO3									
TO4							3.75		
TO5						3.75			
TO6						3.75	3.5		
TO8						3.75	2.5		
TO9									
TO10									
TO11									
CU1									
CU2									
CU3							17.5		
CU4									
CU5									
CU6							17.25		
CU7					15		17.5		
CU9					15			15.75	
CU10					15				
CU11								15.5	
CU12					15			12.25	
CU13					15			15.5	
CU14					13		17.75		
CU15									7.25
CU16					13		17.75		7.25
CU17							17.75		7.25
CU18							17.75		7.25
CU19							16.75		

Storm	10	11	12	13	14	15	16	17	18
Dates	Jan 13-14	Jan 20-21	Jan 22-23	Jan 25	Feb 1-3	Feb 3	Feb 6-8	Feb 9-10	Feb 15
SITES									
CU20									7
CU21							13.75		
CU22									
CU23					13				
CU24					13.75				
CU25									
CU26					13				
CU27									
CU28									
CU29					13				7
SU1									
SU2				9.5	5	6			
SU4			13.25		5	6			
SU5					6				
SU7				10.5	4.25				
SU9				10.5	3.75				
SU11		22.75		7			54.75		
SU12	14	22.75		10.75	39.75		55		
SU14				10.5		6			
SU15			13.75	7.5	5.5	6	22.5		
SU19									
SU20									
SU21									
SU23		22.75		10.25			54.75		
SU24							55.75		
SU25		22.25		10.25			53.75		
SU27									
SU28									
SU29									
SU30									
SU32									

Storm	10	11	12	13	14	15	16	17	18
Dates	Jan 13-14	Jan 20-21	Jan 22-23	Jan 25	Feb 1-3	Feb 3	Feb 6-8	Feb 9-10	Feb 15
SITES									
SU33									
SU34							45		
Storm Total	14	90.5	27.0	86.75	236.0	35.25	505.0	59.0	43.0

Table B-3
Generator Hours – Central and Southern Utah, 2023-2024
Storms 19-27

Storm	19	20	21	22	23	24	25	26	27
Dates	Feb 20-21	Feb 26-27	Mar 3-4	Mar 7	Mar 12-13	Mar 15-16	Mar 24	Mar 25	Mar 26
SITES									
TO1					5.25				
TO2					5.25				
TO3					5.25				
TO4									
TO5					5.25				
TO6					5.25				
TO8		10							
TO9		9.75			5				
TO10									
TO11									
CU1									
CU2	5.25		15.25		10.25				
CU3	5.5		17		11.5				
CU4	4.5				11.5				7
CU5			17		11.5				
CU6	5.25				4				
CU7					3				
CU9			17						
CU10	5.5		16.75		4				
CU11	5.25		17		4				
CU12	5.25				4				
CU13				5	4				
CU14	4.25	10	16.75		11.5				
CU15		10	16.75						
CU16			16.75		12				
CU17	5	10	16.5						
CU18		10			11.5				

Storm	19	20	21	22	23	24	25	26	27
Dates	Feb 20-21	Feb 26-27	Mar 3-4	Mar 7	Mar 12-13	Mar 15-16	Mar 24	Mar 25	Mar 26
SITES									
CU19	5	10	16.75					4.25	
CU20			16.5					5.25	7
CU21		10	16.5		11.5				
CU22		10	15.5						
CU23		10	16.5		11			5.5	5.25
CU24		10	16.5		9.75			5	
CU25									
CU26		10	16.25	5	11				6.75
CU27		11	16.25						
CU28		10	16.25		4				
CU29	4.75	10	16.5		11.5				6.75
SU1									
SU2				6.5			6.75		
SU4									
SU5									
SU7	5.25						6.75		
SU9				5.25			5.75		
SU11					18.5	21.75			
SU12	17.5			6.75			7.75		
SU14							6.75		
SU15									6
SU19									
SU20				5.75	10				3.25
SU21									
SU23				6.5					
SU24						23			
SU25	16.5			7		23			
SU26									
SU27									
SU28									
SU29	3.75				10	23.5			

Storm	19	20	21	22	23	24	25	26	27
Dates	Feb 20-21	Feb 26-27	Mar 3-4	Mar 7	Mar 12-13	Mar 15-16	Mar 24	Mar 25	Mar 26
SITES									
SU30	4								
SU31									
SU32	5				12	23			
SU33					10.5	23			
SU34						20			
Storm Total	**107.5**	**150.75**	**330.25**	**47.75**	**253.75**	**157.25**	**33.75**	**20.0**	**42.0**
LBS Extension						**157.25**	**33.75**	**20.0**	**42.0**

Table B-4
Generator Hours – Central and Southern Utah, 2023-2024
Storms 28-29

Storm	28	29	Site Totals
Dates	Mar 30-31	Apr 6	
SITES			
TO1			19.75
TO2			19.25
TO3			5.25
TO4			29.25
TO5			40.50
TO6			37.00
TO8			32.25
TO9			31.00
TO10			7.25
TO11			0
CU1			0
CU2			45.50
CU3			84.25
CU4			42.75
CU5			77.75
CU6			56.50
CU7			74.00
CU9			76.50
CU10			87.25
CU11			60.00
CU12			80.00
CU13			70.50
CU14			118.50
CU15			85.25
CU16			100.00
CU17		7.75	97.75

Storm	28	29	Site Totals
Dates	Mar 30-31	Apr 6	
SITES			
CU18		8.75	116.00
CU19		8.75	114.00
CU20		8.5	99.50
CU21			105.50
CU22		8.5	80.75
CU23		8	119.00
CU24		8.5	103.25
CU25			52.00
CU26		8.5	110.00
CU27			53.25
CU28			36.25
CU29		8.75	111.25
SU1			11.00
SU2			55.50
SU4			24.25
SU5			6.00
SU7			59.25
SU9			25.25
SU11	23		222.50
SU12	22.25		225.00
SU14	13.5		76.00
SU15			77.75
SU19			0
SU20			44.25
SU21			0
SU23			148.50
SU24	17.75		96.50
SU25	22.25		194.25
SU26			0
SU27			0

Storm	28	29	Site Totals
Dates	Mar 30-31	Apr 6	
SITES			
SU28			33.25
SU29			48.25
SU30			21.50
SU32			57.50
SU33			51.00
SU34	14.75		97.25
Storm Total	113.5	76.0	4053.50
LBS Extension	113.5	76.0	285.25

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

Site	Lat(N)	Long(W)	Elev (Ft)
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

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/airmass: 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.

Atmospheric River/AR: A long, narrow and transient corridor of strong horizontal water vapor transport that is typically associated with a low level jet stream ahead of the cold front of a low pressure system. The water vapor in ARs is supplied by tropical and subtropical moisture sources and frequently produces heavy precipitation where they are forced upward, e.g., by mountains or dynamic lifting.

Balloon Sounding: see Sounding.

Cell: in radar usage, a local maximum in radar reflectivity that undergoes a life cycle of growth and decay, having both an updraft and a downdraft region.

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.

Cyclonic Flow: Counter-clockwise motion, primarily around low pressure (cyclone).

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.

Disturbance: see Low pressure, shortwave.

Dry slot: A zone of dry (and usually cloud-free) air that wraps into the southern and eastern parts of a low pressure system; easily viewed on satellite imagery.

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 Niño: 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).

Frontal band: A band of clouds/precipitation along a cold or warm front.

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 indicates 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.

Infrared (satellite): imagery sensed in the 3-13 µm wavelength region of the electromagnetic spectrum, usually referring to the thermal infrared region.

Inside Slider: A trough or area of low pressure that moves south-southeast along or parallel to the Sierra Nevada mountains before swinging east into the Great Basin or Desert Southwest. These systems typically do not have much moisture with them but can have cold to very cold air accompanying them. The track of these systems typically brings Santa Ana winds as they increase the northeast-southwest pressure gradient.

Inversion: Refers to a layer of the atmosphere in which the temperature increases with elevation, usually associated with stability.

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 Niña: 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 low 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 (counterclockwise) 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.

Mid-level: the layer of the atmosphere from 10-20 kft.

Millibar (mb): a unit of pressure equal to 100 newtons per square meter (N/m^2).

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 (e.g., 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 disturbance): 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.

Sounding: A measurement of the vertical distribution of physical properties of the atmospheric column such as temperature, dewpoint, pressure, wind speed and direction. Soundings are typically conducted by releasing a balloon filled with hydrogen or helium with instrumentation attached that measures different properties as the balloon rises from the surface until it pops at very high altitudes (80-100 kft).

Stable layer: A layer of given thickness in the atmosphere where temperatures are constant with height or rise with height; this results in little to no vertical movement of the air and little to no turbulence/mixing.

Storm Track (sometimes referenced 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.

Subtropical/subtropics: Referring to the region of the Earth bordering on the tropics, from the Tropic of Cancer/Capricorn (23.5°N/S) to about 35°N/S. **Subtropical moisture** would refer to moisture whose source region is the subtropics. **Subtropical Jet Stream** would refer to a jet stream within the subtropics.

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 (counterclockwise) circulation pattern in the Northern Hemisphere.

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

Unstable air mass: an air mass wherein a perturbation (wave) increases in magnitude over time. A parcel of air displaced upward in an unstable airmass will continue to rise until it reaches equilibrium. Regions where, if moisture is sufficient, convection can develop if a mechanism (e.g., heating, frontal boundary) is present to initiate lift.

Upper level: The region of the atmosphere above 20 kft and below the tropopause (approx. 60-80 kft).

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.

Upper level low/trough/disturbance: an area of low pressure located at higher altitudes, e.g., at 700 mb / 10,000 feet MSL or 500 mb / 18,000 feet MSL.

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

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

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

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

Wave clouds: Clouds that form on the rising branches of mountain waves created within a stable airmass in strong flow downwind of mountains. On satellite imagery, they appear as spaced bands of clouds parallel to and downwind of the mountain barrier.