Annual Cloud Seeding Report

Western Uintas Program

2022-2023 Winter Season

Prepared For:

Weber Basin Water Conservancy District

Central Utah Water Conservancy District

Provo River Water Users Association

State of Utah, Division of Water Resources

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NAWC INC

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EXECUTIVE SUMMARY

A total of 26 winter seasons of cloud seeding have been conducted in portions of the Western Uinta Range in Utah. The Western Uintas program utilizes 11 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. The areas targeted for seeding have included the upper portions of both the Weber River and the Provo River drainages in most years.

Precipitation and snowfall were well above normal during the 2022-2023 winter season, with snow water equivalent for the Weber-Ogden River Basin averaging about 198% of the median value on April 1st. The water year precipitation through April 1st averaged 159% of the normal median value across the basin. The Provo River basin had corresponding April 1st averages of 207% of median snowpack and 170% of median precipitation.

A total of 1332 CNG hours were conducted during 22 storm periods this season, out of a maximum budgeted 1,500 hours. By late March, it became apparent that flooding risks outweighed further benefits of the seeding program this season. Although higher elevation SNOTEL sites that have been established by the Division of Water Resources for program suspension criteria in this area were still below their pre-defined suspension thresholds, it was observed that the lower elevation snowpack in each drainage basin were reaching unprecedented highs. Given this, and the continued unseasonably cold weather into the spring season, the seeding program was suspended and ended for the season a week early on March 24.

Evaluations of the effectiveness of the cloud seeding program were made for both the 2022-2023 winter season as well as the past 2 seeded winter seasons combined. These evaluations utilize SNOTEL records collected by the Natural Resources Conservation Service (NRCS) at selected sites within and surrounding the seeded target area. Analyses of the effects of seeding on target area precipitation and snow water content have been conducted for this seeding program, utilizing target/control comparison techniques.

Target and Control studies have been conducted after each season of operations. These studies use linear and multiple linear regressions to compare seasonal performance in seeded areas vs non-seeded areas. **The results of these evaluations, for the past 24 years, point to an average increase of 3% to 6% in April 1st snowpack (as measured by liquid water equivalence) resulting from cloud seeding. This equates to an average increase in runoff of roughly 25,000 acre-feet in the target areas.** It should be noted that, when snowfall for a given season is far lower than average due to abnormal meteorological activity (as experienced during the 2022-2023 season), the percentage increase in snow water equivalence resulting from cloud seeding generally remains the same. However, the total amount of additional runoff resulting from cloud seeding efforts (as measured in acre-feet of runoff) may be lower. Section 5.0 of the report contains further discussion of these mathematical analyses and estimates of the likely value and cost/benefit ratio of the seeding program.

WEATHER MODIFICATION OVERVIEW

The Science

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

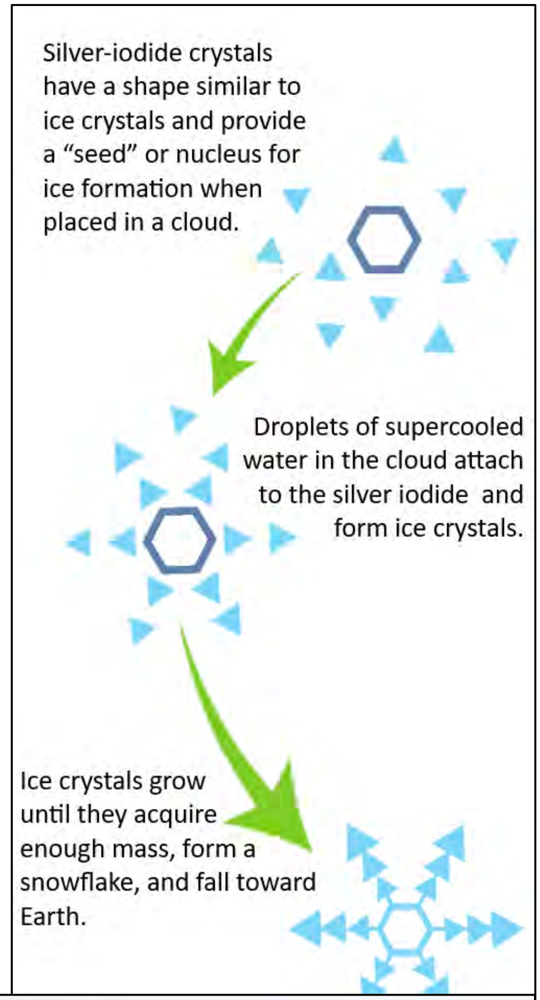
Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.

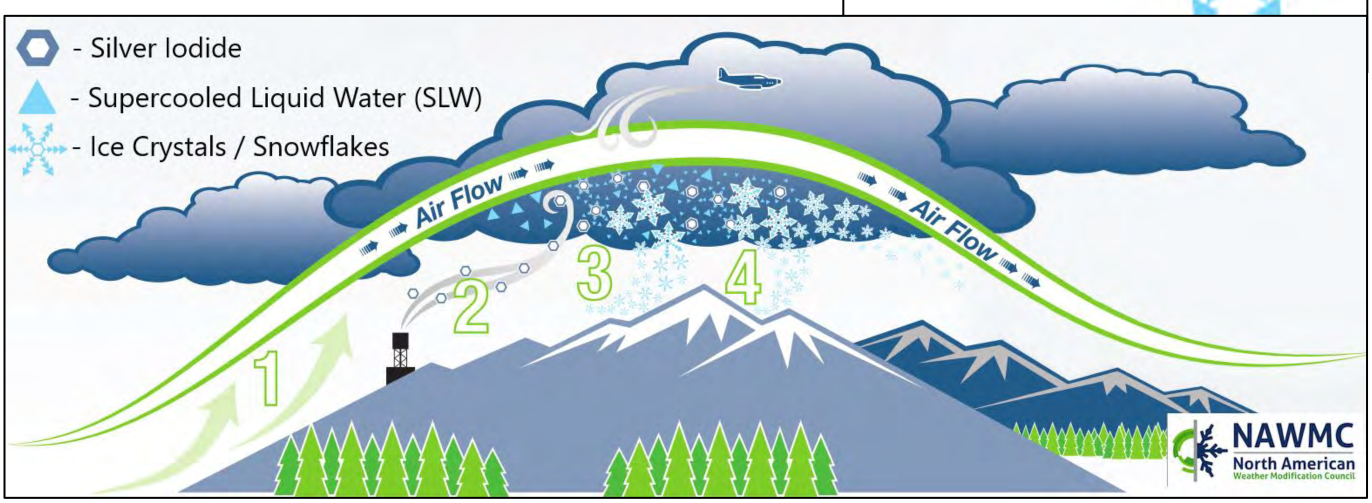
Safety

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

Effectiveness

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





STATE OF THE CLIMATE

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

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

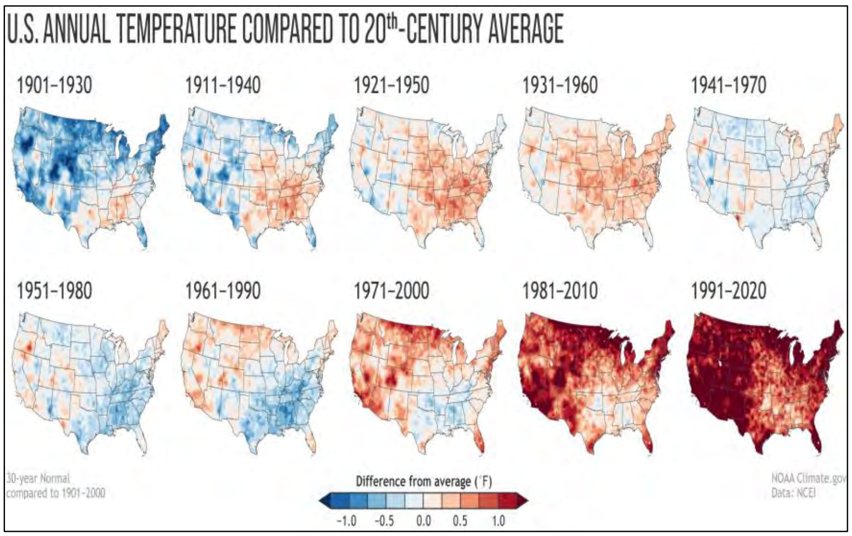


Figure 1 **U.S. Annual Temperature compared to 20th-Century Average**

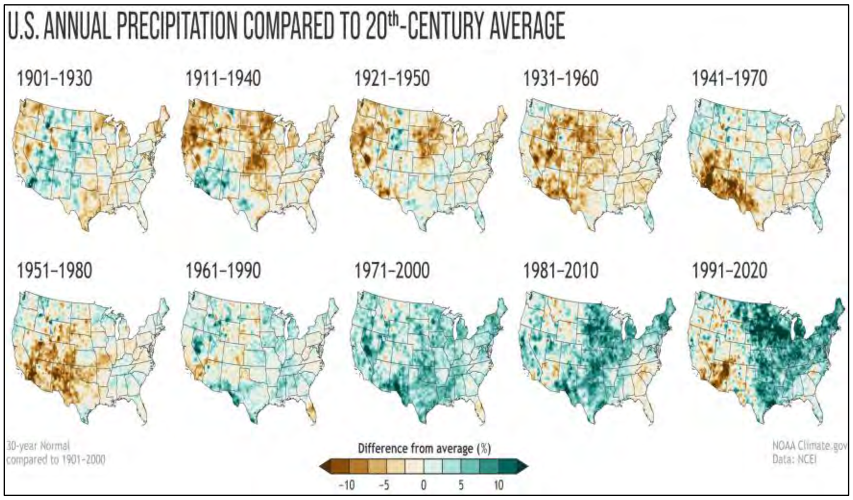


Figure 2 **U.S. annual precipitation compared to 20th-Century average.**

1. INTRODUCTION

Due to high natural precipitation variability and the increasing demand for water, cloud seeding has been conducted in some parts of Utah for over 40 years, helping to augment water supplies. Cloud seeding in Utah is regulated by the Utah Department of Natural Resources through the Division of Water Resources. After complying with various permit requirements, NAWC was granted a license and permit to conduct cloud seeding for the Western Uintas program watersheds. A cloud seeding program was conducted again during the 2021-2022 winter season for the Upper Weber and Provo River Basins. Cloud seeding programs have been conducted in this area by North American Weather Consultants dating back to 1989. These programs have often been jointly sponsored by two agencies: the Provo River Water Users Association and the Weber Basin Water Conservancy District.

The Weber Basin Water Conservancy District's participation has been continuous since the project's inception while the Provo River Water Users Association opted out during water years 2006 to 2012. The Provo River Water Users Association rejoined the program for the 2012-13 season through the present. Eleven ground-based silver iodide cloud nuclei generators (CNGs) were installed for the 2022-2023 season's program. The main program became operational on December 1, 2022 and ended a week early on March 24, 2023. The program was originally contracted to end on March 30, 2023. However, due to the lower elevation snowpack in each drainage basin of the program reaching unprecedented highs, the seeding program was suspended and ended for the season a week early on March 24.

This report provides information about the operational cloud seeding and results of statistical analyses toward estimations of cloud seeding effects. Section 2 describes the seeding project design and provides maps of the seeded target areas, as well as the locations of the CNGs with which the seeding was conducted. Section 3 discusses the types of real-time and forecast meteorological data that are used for conduct of the seeding programs. Section 4 summarizes the seeding operations conducted during this past season. Section 5 details statistical evaluations of the effects of the cloud seeding program.

2. PROGRAM DESIGN

2.1 Background

The operational procedures utilized for this cloud seeding project are essentially the same as those that have been proven to be effective for over 40 years of wintertime cloud seeding in the mountainous regions of Utah (Griffith et al., 2009). The results from these operational seeding efforts have consistently indicated long-term average increases in wintertime precipitation and snow water content during the periods in which cloud seeding was conducted. These estimated increases have generally ranged from 5 to 10 percent more than what would have been expected in the absence of seeding, as predicted by historical linear regression target/control analyses.

2.2 Seeding Criteria

Project operations have utilized a selective seeding approach, which has proven to be the most efficient and cost-effective method, and has provided the most beneficial results. Selective seeding, or seeding only of storms or portions of storms in which precipitation has a reasonable chance of being enhanced, is based on several criteria which determine the seedability of the winter storms. These criteria deal with key characteristics of the air mass (temperature, thermodynamic stability, wind flow and moisture content), both in and below the precipitating clouds. The following list includes some of the key meteorological conditions that generally qualify an event for cloud seeding.

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

2.3 Equipment and Project Set Up

In the fall of 2022 NAWC reinstalled ground-based cloud seeding generators for the winter seeding program. The generators were placed at carefully selected sites, to provide seeding plumes that would be effective in enhancing snowfall over the project target area. Climatological winter storm behavior and prevailing wind direction are major factors in the placement of these sites. Eleven seeding sites were installed for this year's seeding program, whose locations are shown in Figure 2.1. Occasionally, seeding sites installed for other seeding programs in the region (such as Northern Utah and High Uintas programs) are used to target the Western Uintas program during less commonly occurring wind flow situations.

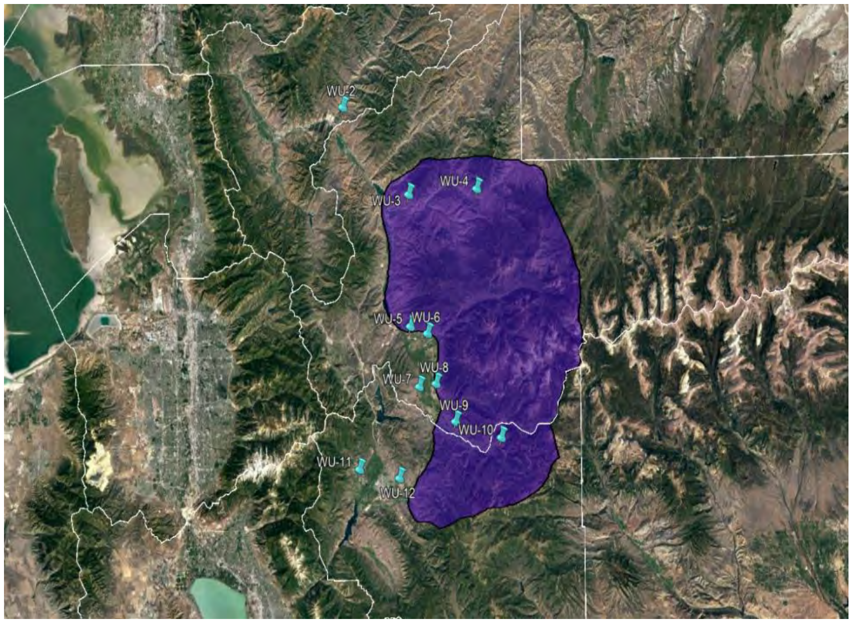


Figure 2.1 **Western Uintas target area (purple) and ground-based cloud seeding generator locations (blue pins).**

Ground-Based Manual Generators

The cloud seeding equipment consists of a cloud nuclei generator (CNG) unit and a propane gas supply (Figure 2.2). The seeding solution, emitted via combustion, consists of two percent by weight silver iodide (AgI), complexed with small portions of sodium iodide and para-dichlorobenzene in solution with acetone.

The seeding unit is manually operated by igniting the propane flame (at the flame head in a burn chamber) and adjusting the flow of seeding solution through a flow rate meter. The propane gas also pressurizes the solution tank, which allows the solution to be sprayed into the CNG's burn chamber at a regulated rate, where microscopic (sub-micron)-sized silver iodide crystals are formed. The crystals, which closely resemble natural ice crystals in structure, are released at a rate of 8 grams per hour per generator when using the 2% solution. These crystals become active as artificial ice nuclei in-cloud at temperatures between -5°C (23°F) and -10°C (14°F).

It is necessary that the AgI crystals become active in the formation zone (the region in the cloud which contains supercooled liquid water) upwind of, or over the project area mountain crest. This allows the available supercooled liquid water to be effectively converted to ice crystals which grow to snowflake size and precipitate onto the mountain barrier within the intended area of effect. If the AgI crystals take too long to become active, or if the temperature upwind of the crest is too warm, the seeding plume will pass from the generator through the precipitation formation zone and over the mountain crest without producing any additional snowfall at the surface. It is the meteorologist's task to identify storm situations in which the seeding treatment can be effective.

Figure 2.2 **Manually operated cloud seeding generator**

Cloud seeding generators were sited at 11 locations (mostly in the valleys), ranging from the southwest to northwest sides of the target area, as shown in Figure 2.1. Pertinent CNG site information is provided in Table 2-1. Most of the winter storms that affect the northern Utah Mountains are associated with synoptic weather systems that move into Utah from the northwest, west or southwest. Usually, they consist of a frontal system and/or an upper trough with the winds preceding the front or trough blowing from the south or southwest. As each system passes through the area, the wind flow changes to the west, northwest, or north. Clouds and precipitation may precede as well as follow the front/trough passage, or they may occur primarily after the passage along the boundary of the colder air mass that moves into the region. For the region comprising the project target area, the most abundant precipitation and low-mid level moisture usually occurs in west to northwest flow patterns. This is when the best seeding opportunities typically occur. Southwesterly flow is generally associated with somewhat warmer conditions that are sometimes less seedable.

Table 2-1
Cloud Seeding Generator Sites

Site ID	Site Name	Elev (Ft)	Lat (N)	Long (W)
WU-2	Croyden	5371	41° 04.12'	111° 30.83'
WU-3	Coalville	5587	40° 55.95'	111° 20.72'
WU-4	Pineview	6407	40° 56.39'	111° 10.18'
WU-5	Peoa	6148	40° 43.75'	111° 20.61'
WU-6	Oakley	6472	40° 43.07'	111° 18.00'
WU-7	Kamas West	6872	40° 38.16'	111° 19.33'
WU-8	Kamas	6489	40° 38.43'	111° 16.77'
WU-9	Woodland	6706	40° 34.89'	111° 13.81'
WU-10	Woodland East	7305	40° 33.35'	111° 06.80'
WU-11	Midway	5570	40° 30.59'	111° 28.64'
WU-12	Heber City	5810	40° 29.73'	111° 22.52'

2.4 Suspension Criteria

NAWC always conducts its projects within guidelines adopted to ensure public safety. Accordingly, NAWC has a standing policy and project-specific procedures for the suspension of cloud seeding operations in certain situations. Those criteria are shown in Appendix A and have recently been updated in coordination with the Utah Division of Water Resources. The criteria are an integral part of the seeding program. **By late March, it became apparent that flooding risks outweighed further benefits of the seeding program this season. Although higher elevation SNOTEL sites that have been established by the Division of Water Resources for program suspension criteria in this area were still below their pre-defined suspension thresholds, it was observed that the lower elevation snowpack in each drainage basin were reaching unprecedented highs. Given this, and the continued unseasonably cold weather into the spring season, the seeding program was suspended and ended for the season a week early on March 24, 2023.**

3. WEATHER DATA AND MODELS

NAWC maintains a fully equipped project operations center at its Sandy, Utah headquarters. Meteorological information is acquired online from a wide variety of freely available sources and subscriber services. This information includes weather forecast model data, surface observations, rawinsonde (weather balloon) upper-air observations, satellite images, NEXRAD radar information, and weather cameras. This information helps NAWC's meteorologists to determine when conditions are appropriate for cloud seeding. NAWC's meteorologists are able to access all meteorological products from their homes, allowing continued monitoring and conduct of seeding operations outside of regular business hours.

Figures 3.1 – 3.3 show examples of some of the available weather information that was used in this decision-making process. Figure 3.4 displays predictions of ground-based seeding plume dispersion for a discrete storm period in the Western Uintas Program from the 2022-2023 season using the National Oceanic and Atmospheric Administration's HYSPLIT model. This model helps to estimate the horizontal and vertical spread of a plume from potential ground-based seeding sites based on wind fields contained in the weather forecast models.

Global and regional forecast models are a cornerstone of modern weather forecasting, and important tools 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 from the global GFS forecast model for a storm event during the 2022-2023 season is shown in Figure 3.5.

During the summer of 2022, NAWC built an in-house Python script that has the ability to ingest 3-km High-Resolution Rapid Refresh (HRRR) model data readily available online. This script allows the user to define a grid where seeding operations and liquid water could be occurring. The user can specify a cross section over any location in the continental U.S. or Canada. This model data was used during cloud seeding operations as guidance. In these cross sections, liquid water is plotted as a function of distance and height, with temperatures (red dashed lines), wind directions and speed (wind barbs) and potential temperatures (solid black lines) also being displayed. This model was utilized in a variety of different areas where NAWC conducts cloud seeding operations. The script has the ability to be run for one specific forecast hour. Figure 3.6 shows an example of the cross-section plot during a seeded event from this past winter season that includes liquid water occurrence, temperature, wind direction, wind speed and potential temperatures as a function of height. The map inset located in the upper left corner of the cross-section plot shows a map of where the cross section was taken within the state of Colorado. It is important to notice how much of the predicted liquid water is tied to underlaying terrain due to orographic forcing (lifting of the airmass as winds force it over the underlaying terrain). Also notice that much of the predicted liquid water is at temperatures of -5° C or colder which is an important feature since the silver iodide nuclei released from the remote generators mush reach this level in order for the nuclei to become active freezing nuclei. This model will continue to be utilized in future winter seasons and possibly lead to further verification techniques.

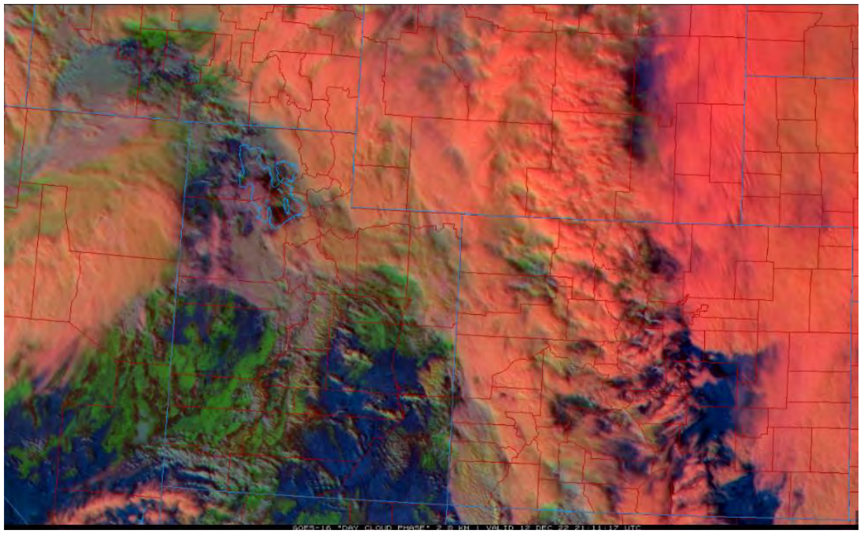


Figure 3.1 **Day Cloud Phase satellite image of Utah during the afternoon of December 12, 2022 during a seeded event.**

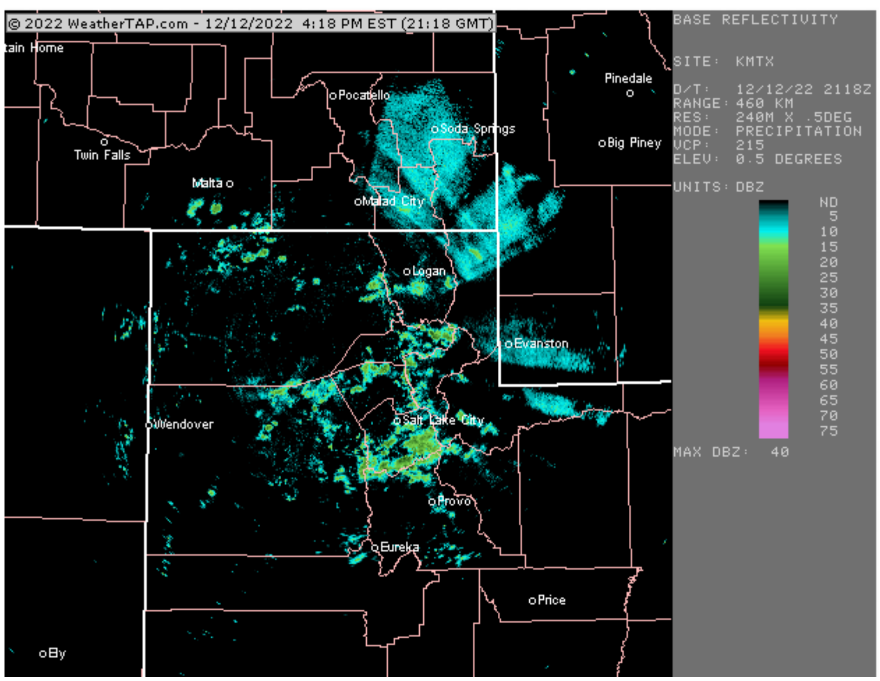


Figure 3.2 **Weather radar image over northern Utah during the afternoon of December 12, 2022. Image courtesy of weatherTAP.com.**

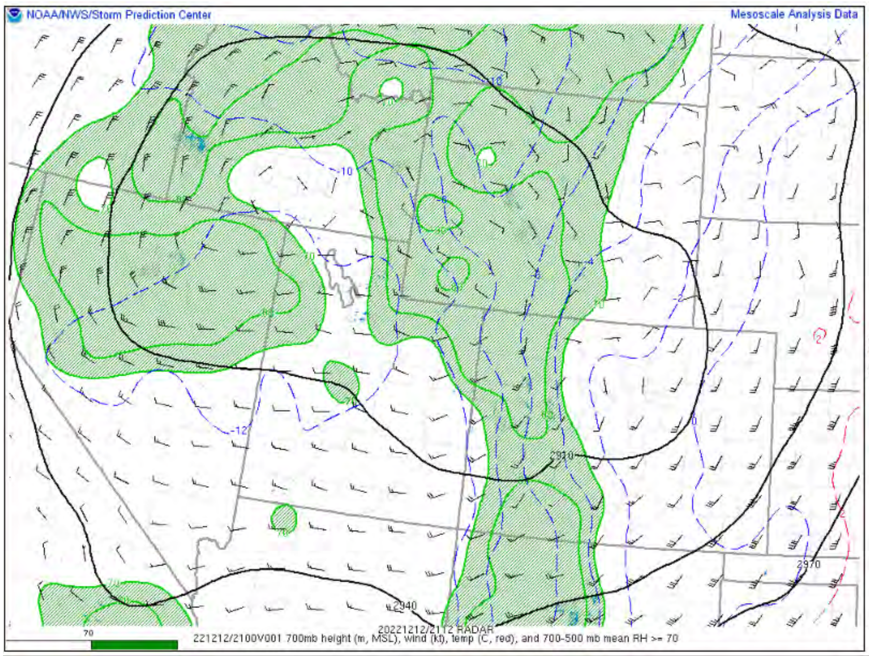


Figure 3.3 U.S. 700 mb map during the afternoon December 12, 2022, illustrating the larger scale weather pattern across the region.

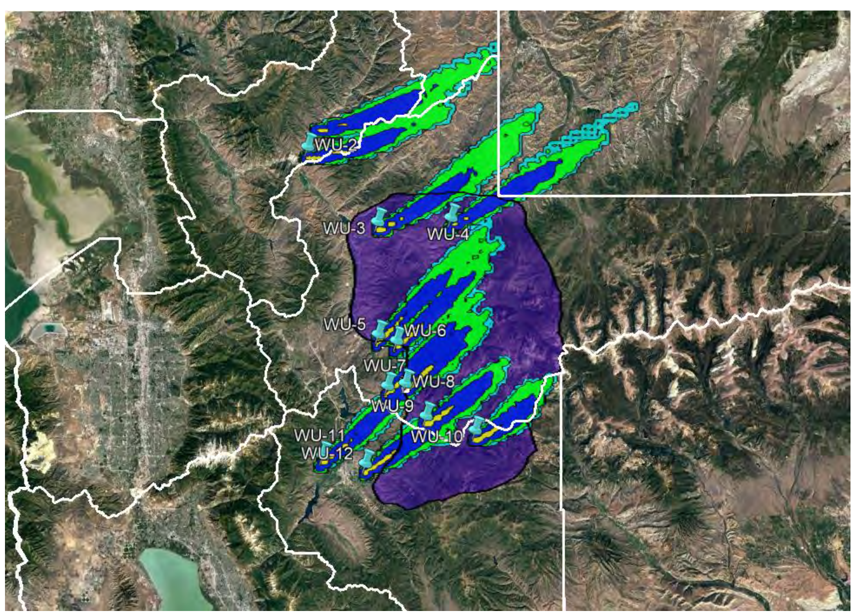
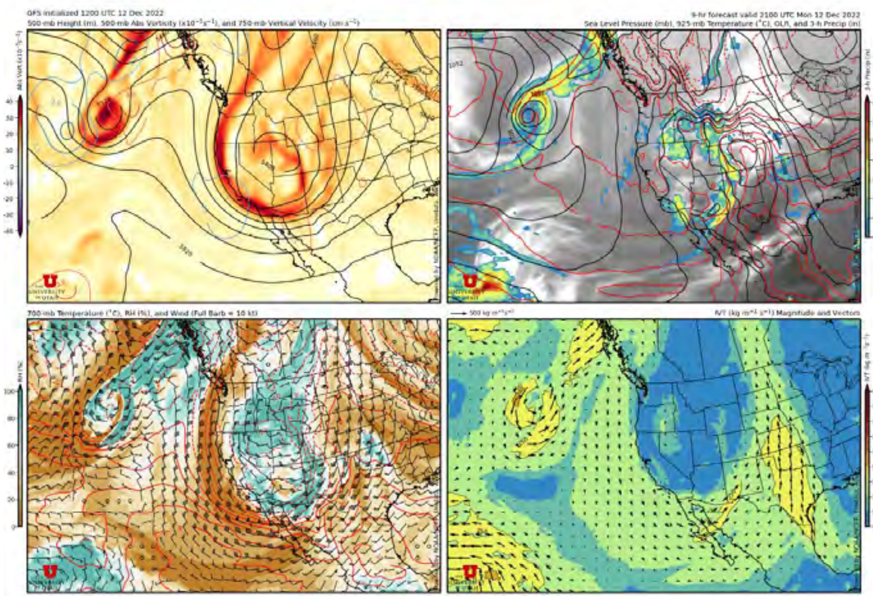


Figure 3.4 HYSPLIT plume dispersion forecast from individual ground generator sites during a storm period during the afternoon on December 12, 2022 from all potential sites.



Figures 3.5 **GFS (Global Forecast Systems) 4-Panel model plot during the storm event on the afternoon of December 11-13, 2023.**

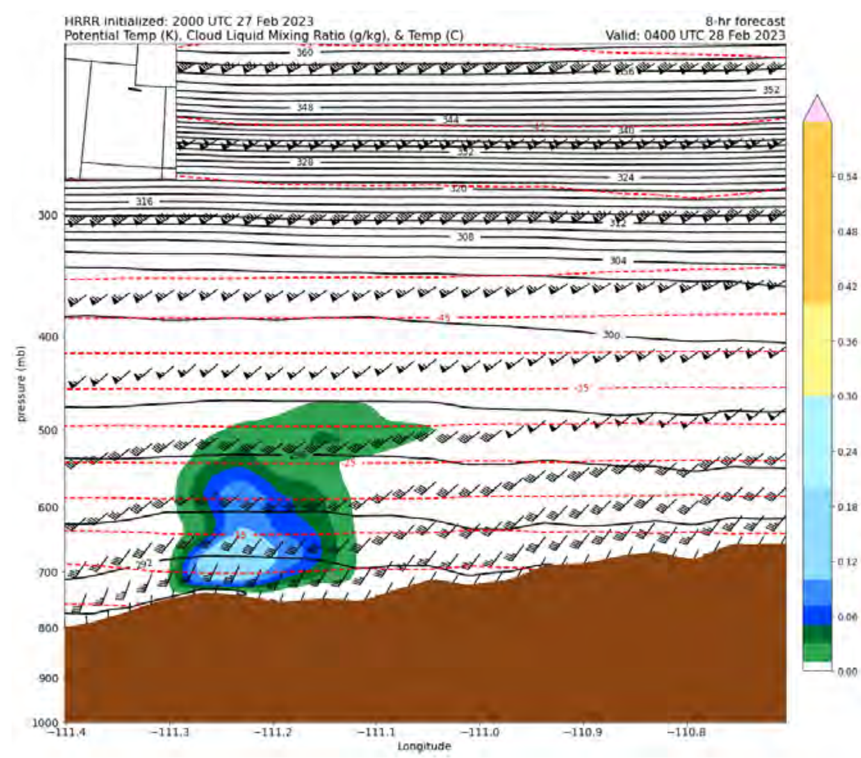


Figure 3.6 **HRRR modeled Cross Section of Liquid Water on February 27, 2023 – Valid at 2100 MST**

4. OPERATIONS

The 2022-2023 Western Uintas cloud seeding program for the Weber and Provo River basins began on December 1, 2022, and ended on March 24, 2023. The program was originally contracted to end on March 30, 2023. However, due to the lower elevation snowpack in each drainage basin of the program reaching unprecedented highs, the seeding program was suspended and ended for the season a week early on March 24. A total of 22 storm periods were seeded during all or portions of 31 days: five storms were seeded in December, five in January, five in February, and seven in March. A total of 1330 seeding generator hours were conducted this season. Table 4-1 shows the dates and ground generator usage for the storm events, and Appendix B contains more detailed site usage data. Figure 4.1 shows the usage of generator hours during the season.

Precipitation and snowfall were well above normal during the 2022-2023 winter season, with snow water equivalent for the Weber-Ogden River basin averaging about 198% of the median value on April 1. The water year precipitation through April 1 averaged 159% of the normal (medium value) across the basin. The Provo River basin had corresponding April 1 averages of 207% of median snowpack and 170% of medium precipitation. Figures 4.2 to 4.4 are seasonal graphs for some SNOTEL sites in the target area.

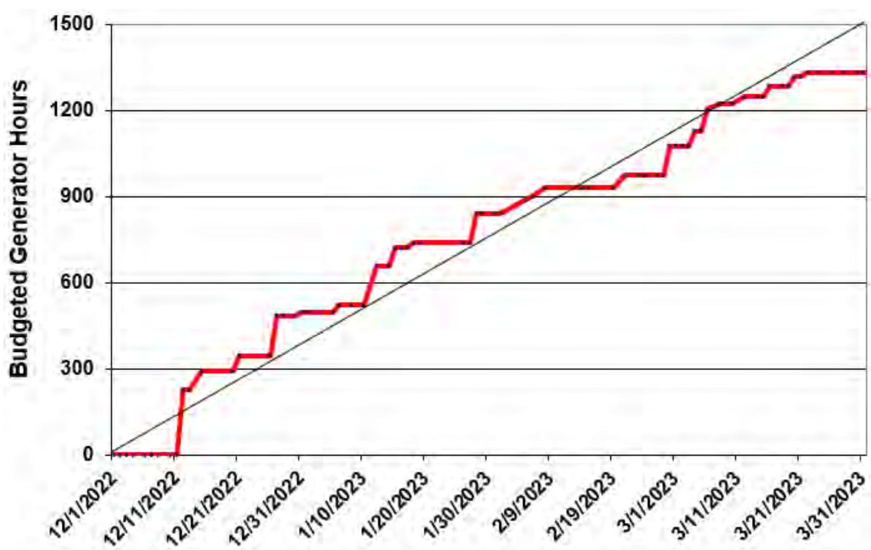


Figure 4.1 **Seeding during the 2022-2023 season (red), in comparison to a linear usage of budgeted hours through the season (diagonal line).**

Table 4-1
Storm dates and number of generators used, 2022-2023 season.

Storm No.	Date(s)	No. of Generators Used	No. of Hours
1	December 11-13	8	224.75
2	December 15	7	65
3	December 21	6	54.5
4	December 27-28	8	139
5	December 31	2	13.5
6	January 6	3	23
7	January 10-11	8	138.75
8	January 15	8	62.5
9	January 17-18	1	17.25
10	January 27-28	5	102
11	February 5	7	45.25
12	February 6	3	13
13	February 8	6	30
14	February 21	7	43.25
15	February 27-28	8	102.5
16	March 4-5	4	56
17	March 5-6	6	76
18	March 8	4	18
19	March 12	5	25
20	March 15	4	37
21	March 20	4	32
22	March 22	2	15.75
Season Total	---	---	1330

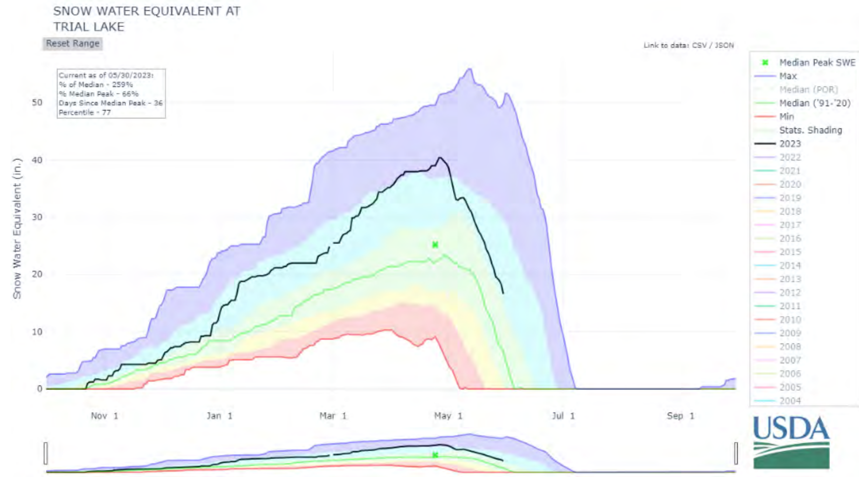


Figure 4.2 **NRCS SNOTEL snow water content plot for October 1, 2022 through May 30, 2022 for the Trial Lake, UT SNOTEL Site. Black line is the 2022-23 season data. Green represents the median, while purple and red are the historical max and min values respectively.**

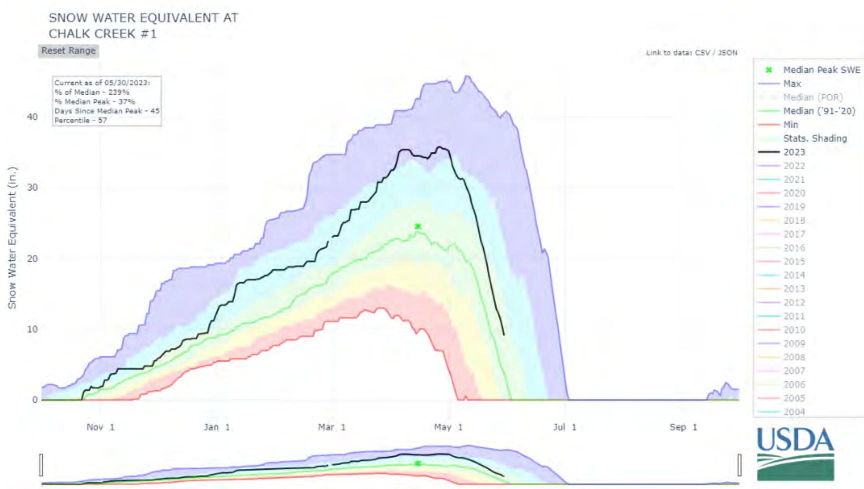


Figure 4.3 **NRCS SNOTEL snow water content plot for October 1, 2022 through May 30, 2023 for Chalk Creek #1, UT SNOTEL site. Black line is the 2022-23 season data. Green represents the median, while purple and red are the historical max and min values respectively.**

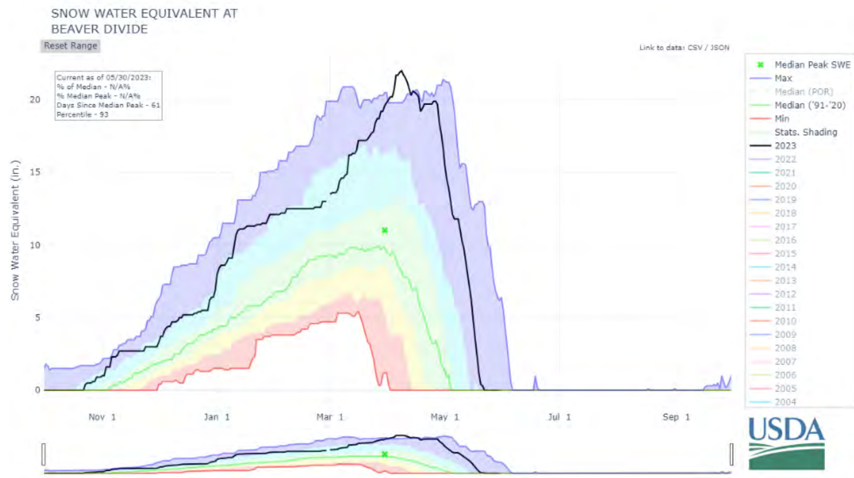


Figure 4.4 **NRCS SNOTEL snow water content plot for October 1, 2022 through May 30, 2023 for Beaver Divide, UT SNOTEL site. Black line is the 2022-23 season data. Green represents the median, while purple and red are the historical max and min values respectively.**

In operational practice, the project meteorologist, with the aid of continually updated online weather information, monitored each approaching storm. If the storm parameters met the seedability criteria presented in Table 2-1, and if no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators was ignited and then adjusted as evolving conditions required. Seeding continued as long as conditions were favorable and precipitating clouds remained over the target area. The operation of the seeding sites is not a simple "all-or-nothing" situation. Individual seeding sites are selected and run based on their location, and targeting considerations based on storm attributes.

4.1 Operational Summary

A brief synopsis of seeded (or otherwise significant) storm events during the operational seeding period is provided below. All times are local (MST/MDT) unless otherwise noted. References to wind direction in meteorology correspond to the direction that the wind is coming from (the upwind direction). The 700 mb level (~9,500 feet above sea level during the winter) temperature in the atmosphere is often referenced, given that the temperature near mountain crest height is an important consideration for cloud seeding.

<u>**December 2022**</u>

The month of December 2022 featured an active weather pattern and above normal precipitation/snowfall. There were five seeded storm events during the month. Figure 4.5 shows December 2022 precipitation across the region as a percentage of average (mean) monthly totals.

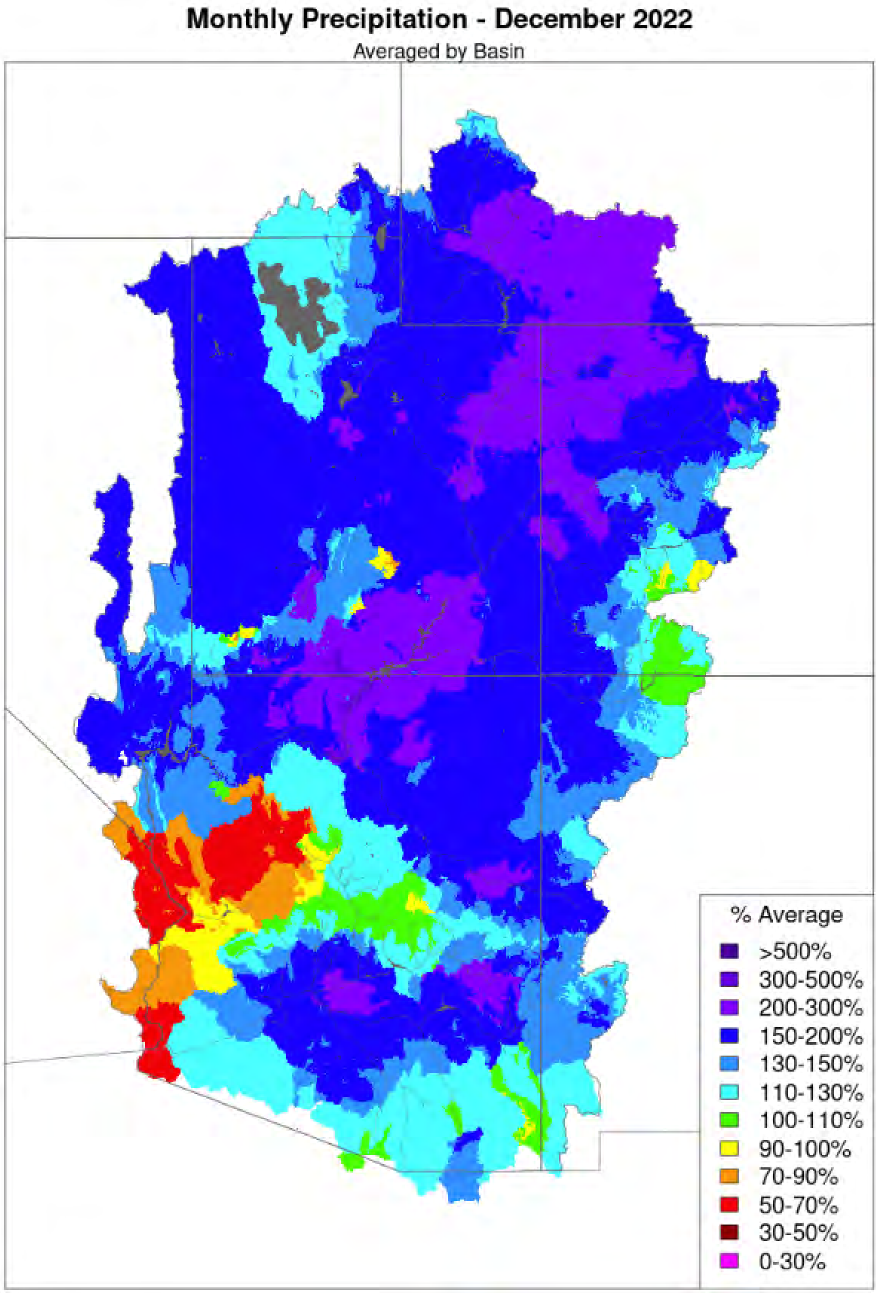


Figure 4.5 **December 2022 precipitation, percent of normal**

The weather pattern on December 11th consisted of a deep trough that enveloped California and the entire Great Basin Region. Strong, dry and warm southerly flow was occurring across Utah ahead of this large trough and its associated cold frontal boundary. 700mb temperatures through the afternoon hours on the 11th climbed up to near -2°C and southerly winds were gusting upwards of 45-55 knots. The associated frontal boundary finally pushed eastward and across the program area after 1800 MST on the

11th which allowed a broad area of moderate to heavy snow to fill in over northern Utah. 700mb temperatures dropped to near -9°C overnight into the morning hours of the 12th, but the flow continued to remain southerly. Several seeding sites that are favorable in a southerly flow regime were turned on at 1830 MST on the 11th and remained on overnight into the morning of the 12th. As the core of the large trough moved overhead Utah, then downstream into Colorado on the 12th into the 13th, the flow shifted northwesterly and additional moisture was funneled into northern Utah. This allowed snow showers to continue across the program area throughout the 12th and into the morning hours of the 13th before drier air finally settled in and snow showers tapered off after 1200 MST on the 13th. Areal observations indicated 0.3-1.0 inches of liquid water equivalent was recorded across the program.

Light snow developed over northern Utah around 0000 MST on the 15th and then continued throughout the morning and early afternoon hours as a weak and quick moving trough slid northwest to southeast across Utah. Moisture was rather limited with this system due to 700mb temperatures being very cold and around -15°C. Even though this was considered a marginal storm, seeding operations were conducted from 0700 MST until snow showers tapered off after 1600 MST. Up to 0.3" of liquid water equivalent were recorded in the target area.

A very cold frontal boundary riding southeast through Wyoming and Colorado delivered a glancing blow to northern Utah during the afternoon and evening of December 21st. Moisture embedded within southwesterly flow ahead of the incoming front allowed spotty snow showers to develop over the program on the morning hours of the 21st, which continued into the afternoon hours. The cold front then arrived in northern Utah around 1600 MST and pushed southward across the western Uintas between 1700-1800 MST. A brief burst of moderate to heavy snow accompanied the frontal passage and winds shifted from southwesterly to northwesterly. Temperatures also quickly dropped with the passage of the front with 700mb temperatures falling from -8°C to near -18°C. CNG sites were activated in the morning hours of the 21st and continued to run until 2100 MST, when precipitation finally tapered off. Between 0.3 and 0.9 inches of SWE was observed throughout the target area.

A strong Pacific jet streak and attendant Atmospheric River pushed into northern and central California on the 27th. Low-level moisture advection along the leading edge of this plume of moisture spread into northern Utah during the afternoon and early evening hours on the 27th. This brought a period of moderate and heavy precipitation to the area within a mild southwesterly flow regime. Given that 700mb temperatures were around -2°C with this initial surge of moisture, seeding operations were held off. An associated cold front then dropped southward and through Utah on the evening of the 27th, reaching the program around 2000 MST. In the wake of this cold front, a favorable window for orographic snowfall developed underneath a moist and cold northwesterly flow pattern. CNG sites were activated right as the cold front pushed into the target area around 2000 MST on the 27th and ran overnight and through most of the day on the 28th before precipitation finally came to an end after 1800 MST. Up to 1.3" of liquid water equivalent were recorded in the target area.

A strong cold front quickly blasted southeast and across northern Utah during the morning and afternoon hours on the 26th. A convective snow squall developed along the leading edge of the cold front early in the morning on the 26th with warm southwesterly flow in place out ahead of it. As the cold front moved into the Western Uintas during the afternoon on 26th, snow rapidly intensified and became moderate to heavy for a few brief hours. Snow decreased once the cold front passed through the area later in the afternoon, then eventually came to an end early in the evening as the cold front exited Utah. CNG sites were active right as the cold front pushed into the target area and ran into the early evening hours of the 16th before precipitation finally came to an end. Areal observations indicated that up to one inch of liquid water equivalent was recorded.

A positively tilted trough developed over the eastern Pacific Ocean on the morning of December 31st. Ahead of this developing system, an east to west oriented mid-level warm front had become situated over central Utah. As the trough approached Utah during the late morning hours on the 31st, modest moisture transport within a southwesterly flow pattern overran the warm front and caused moderate precipitation to fill in over the program area. Seeding CNG sites were activated on the morning of the 31st as satellite imagery and radar returns revealed that good orographic precipitation occurring as the moisture rich flow was up sloped into the terrain. As the large trough track further east and deepened in the lee of the Sierra Nevada, it forced the flow to turn southeasterly to easterly over the program area during the evening and overnight hours on the 31st. Snow showers continued through the night, but seeding operations were concluded due to the flow no longer being favorable for targeting the program area.

January 2023

The weather pattern remained very active through the month of January and featured several strong storms that brought above average precipitation to the region. Seeding was conducted for the Western Uintas during five storm events in January. Figure 4.6 shows January 2023 precipitation across the state as a percentage of average (mean) monthly totals.

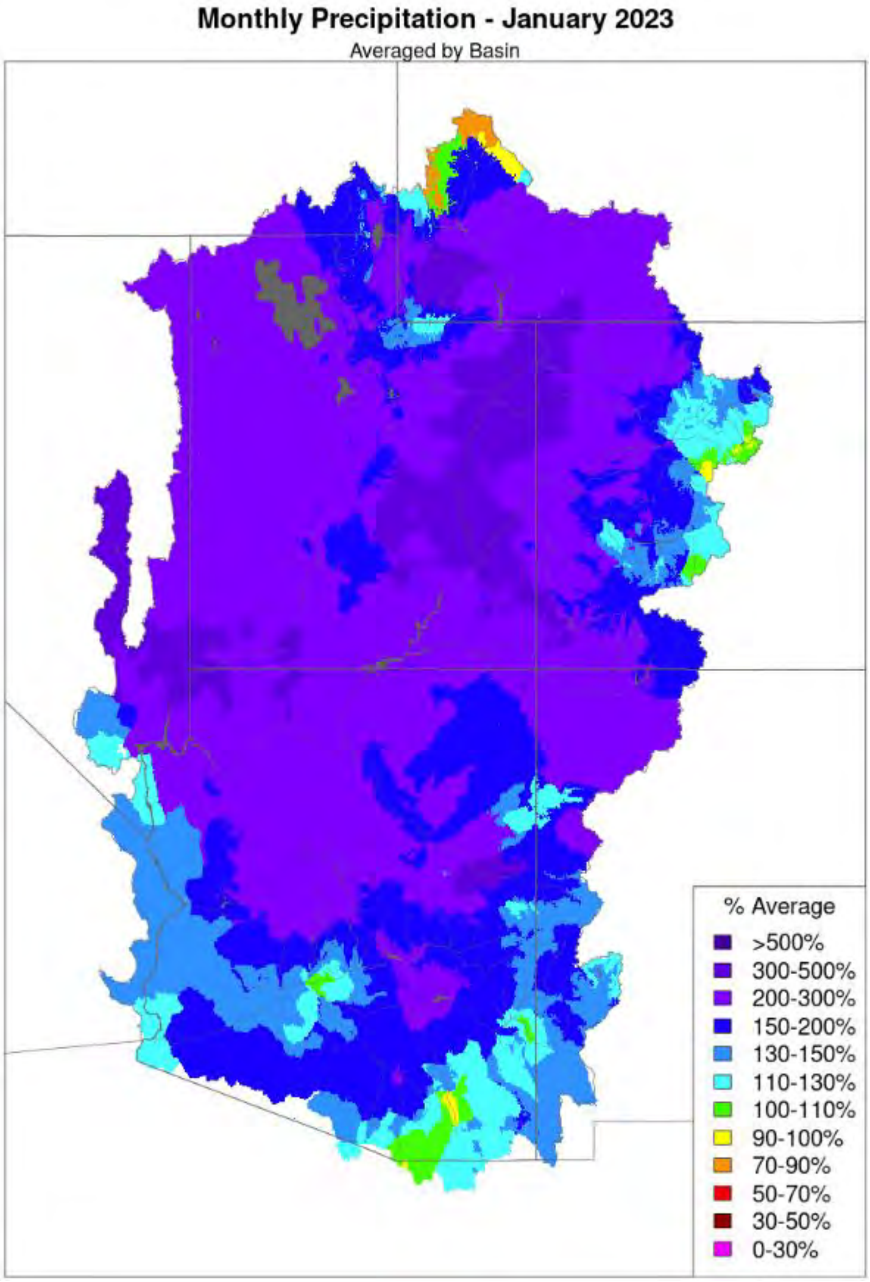


Figure 4.6 **January 2023 precipitation, percent of normal**

A decaying atmospheric river associated with a splitting trough pushed into northern Utah on the evening of January 5th. Warm advection ahead of this atmospheric river was accompanied by an increase in moisture aloft, which led to the development of widespread stratiform snow over northern Utah late in overnight into the early morning hours of the 6th. No seeding activity occurred during the overnight hours of the 5th into the 6th due to 700mb temperatures being on the mild side (around -2/-3°C) and the mid-levels of the atmosphere presenting stability issues. As the open wave trough finally moved downstream into Colorado on the morning of the 6th, the flow aloft shifted from southwesterly to northwesterly and 700mb temperatures cooled to near -8°C. CNG sites were activated on the morning of the 6th and ran through the afternoon hours. By 1800 MST on the 6th, moisture had finally begun to decrease and ultimately led to the end of snow over the area as well as seeding operations. Storm total precipitation was generally in the 0.3-0.5" range (liquid water equivalent).

Utah came under the influence of a rather moist southwesterly flow pattern on the morning of January 10 as the first in a series of troughs slid across the western U.S. Moderate to heavy precipitation developed over northern Utah during the pre-dawn hours on the 10th. No seeding activity occurred with this first round of precipitation due to 700mb temperatures holding near -3°C and the profile of the atmosphere exhibiting strong stability in the lower levels. Precipitation briefly tapered off during the afternoon hours as this first wave exited off to the east. A secondary and much larger trough then pushed a strong cold front eastward and across the area with the front reaching the seeding area around 1800 MST. The front was accompanied by a band of heavy snow, a few lightning strikes, and an abrupt wind shift from southwesterly to northwesterly. 700mb temperatures also fell behind the frontal passage from around -3°C to near -10°C. Seeding CNG sites favorable in northwesterly flow were activated ahead of the frontal passage around 1600 MST and remained on overnight into the morning hours of January 11th. Snow showers then tapered off after 1200 MST on the 11th and it was at this time that seeding activity was concluded. Storm total precipitation ranged from 0.6"-1.3" of snow water equivalent.

An upper-level trough approaching the Great Basin region on the evening of January 14th impinged a moist southerly flow pattern over northern Utah. As a result, widespread precipitation filled in over the program area and continued overnight into the pre-dawn hours of the 15th. No seeding occurred during this overnight period because the Salt Lake City upper air balloon sounding revealed that there was a stable layer present in the mid-levels and the surface flow over the region was more southeasterly than southerly. Snow showers continued throughout the day on the 15th but as the axis of the trough finally passed overhead Utah during the late morning hours, 700mb temperatures fell from near -5°C to near -9°C. and the flow aloft shifted from southeasterly to west/northwesterly. CNG sites were activated during the late morning hours and remained on until snow showers tapered off after 1800 MST. Total snow water equivalent (SWE) for this event ranged from 0.1"-0.3".

An upper-level trough with a few embedded shortwave features made its way across the Great Basin/Desert Southwest region early on the morning of January 17. A deformation band of precipitation developed on the northwestern periphery of this trough axis late in the evening of the 16th and became situated over northwest Utah. Further east and over the seeding area, a dry slot developed and kept conditions dry. No seeding activity occurred from the evening of the 16th into the morning of the 17th due to the wind direction being southeasterly and the dry slot moving overhead around 02/0300 MST. One of the embedded shortwaves then rotated across Arizona and eventually evolved into a closed low across the 4-Corners by late morning/afternoon. As this occurred, the deformation band shifted southeastward and spread snow showers back over the seeding area. CNG sites were activated around 1430 MST as the flow shifted from southeasterly to northwesterly. Snow showers and seeding operations continued through the night and then came to an end after 0800 MST on the 18th after conditions dried out. Total snow water equivalent (SWE) for this event ranged from 0.1”-0.2”.

The last week of January featured an upper-level pattern that consisted of a broad ridge of high pressure across the eastern Pacific with a series of shortwave troughs diving southward out of the Pacific Northwest and into the Great Basin region. One such wave dropped southward and clipped far northeast Utah during the afternoon and evening hours of the 27th. As the wave approached Utah late in the afternoon hours, snow showers began to develop and increase in intensity. Snow showers persisted through the night with the flow remaining northwesterly and 700mb temperatures dropping from -8°C to near -12°C. Seeding CNG sites were activated as soon as snow started increasing around 1500 MST on the 27th. Seeding continued overnight and up until snow showers ended around 1200 MST on the 28th. SWE totals from this event were in the 0.2”-0.6” range.

February 2022

The weather pattern remained quite active through the month of February. A couple of weak storms impacted the area near the beginning of the month which was followed by a period of drier and calmer weather conditions through the mid-month. A long wave trough pattern then developed across the western U.S. starting around February 20/21. This opened the door for an extended period of cold and wet weather, with several significant systems affecting the program through the last week of the month. Five storms were considered suitable for seeding operations during the month of February. Figure 4.7 shows the percentage of normal February precipitation across the region.

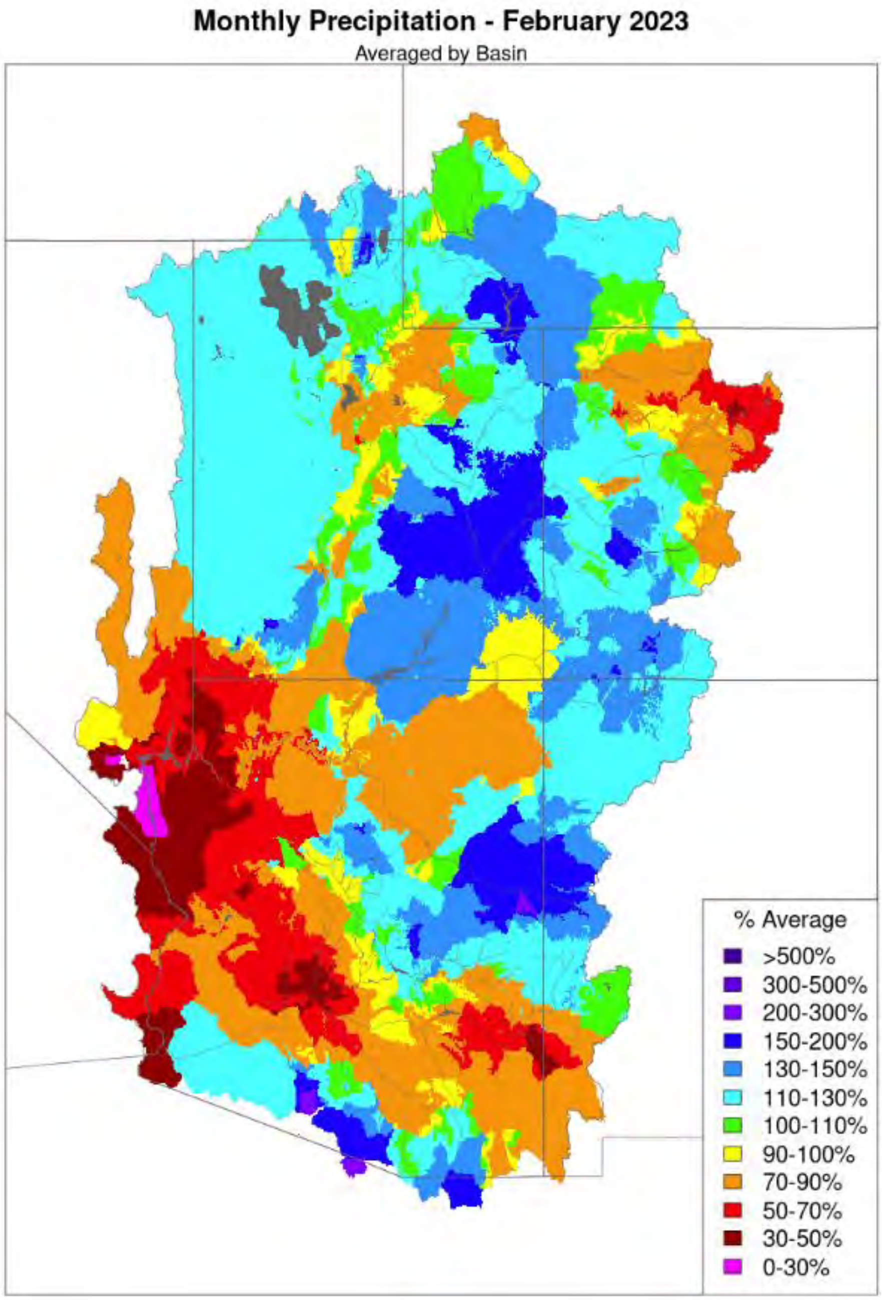


Figure 4.7 **February 2023 precipitation, percent of normal**

A somewhat large and disorganized trough made its way across Nevada and Utah during the afternoon hours of February 5th then continued eastward into Colorado in the evening. A north-to-south-oriented frontal boundary associated with this trough was forced eastward and across Utah. Southerly winds ahead of the front shifted west to northwesterly behind its passage and 700mb temperatures fell to near -12°C.

Snow showers first developed over the program area around 0800 MST on the 5th but initially struggled to reach the surface due to the presence of a dry layer. As the atmosphere moistened up through the afternoon hours, snow showers filled and continued until skies cleared out after 2000 MST. Total snow water equivalent (SWE) for this event ranged from 0.1”-0.4”.

The next in the series of storms began to impact Utah on the morning of February 6th. This next trough dug southward out of Idaho during the early morning hours then pushed off to the south later in the afternoon and evening. As the system dug southward in the early morning hours of the 6th, it brought a reinforcing shot of colder temperatures and a renewed burst of light snow. Light snow shower activity persisted over the area through the early afternoon hours before dissipating and drying out after 1300 MST. Total snow water equivalent (SWE) for this event ranged from 0.1”-0.4”.

A fast-moving cold front swept southward and across Utah during the afternoon hours of the 8th, then quickly exited off to the southeast during the evening. The front turned out to be quite strong as it moved southward and brought a brief period of heavy snow, several lightning strikes, gusty northwesterly winds, and a rapid drop in temperatures. Snow showers and seeding operations first developed around 1500 MST as the cold front moved in and continued until conditions quickly dried out after 2000 MST. Storm total SWE for this event was light and ranged from 0.1-0.3”.

After a week of dry weather, a significant winter storm brought heavy snowfall to the seeding area the 21st into the 22nd. A frontogenetical cold frontal boundary shifted southward into northern Utah during the afternoon of the 21st where it became stalled over the program area overnight into the morning hours of the 22nd. Southwesterly flow ahead of the boundary became disorganized by the evening hours of the 21st with the flow varying from southeasterly to east/northeasterly. This caused the boundary to slowly pivot to more of a southwest to northeast orientation and allowed heavy snow occurring along the boundary to continue overnight. 700mb temperatures slowly fell through the evening of the 21st where they bottomed out near –10/-11°C. Several seeding CNG sites were activated during the early afternoon hours of the 21st and remained on until the flow at the surface became unfavorable after 2000 MST. Total snow water equivalent (SWE) for this event ranged from 0.5-1.2”.

A weak shortwave disturbance grazed far northern Utah overnight on the 26th into the morning of the 27th and brought an increase in moisture within a southerly flow regime. This caused snow showers to develop across the seeding area which continued throughout the morning hours on the 27th. No seeding occurred from the evening of the 26th into the morning hours of the 27th as a stable layer near 700mb was observed to be present on the Salt Lake City upper air sounding. A trailing secondary shortwave trough then pushed eastward out of California and tracked overhead Utah on the evening of the 27th. Precipitation increased in coverage and intensity as this trough moved overhead and cooling 700mb temperatures helped erode the stable layer that had been present all day. Seeding CNG sites were activated around 1800 MST on the

27th and remained on overnight into the early morning hours of the 28th before being turned off as snow showers diminished. Total snow water equivalent (SWE) for this event ranged from 0.5-1.1”.

March 2023

The month of March was very active and featured several significant storm events that brought well above normal snowfall to the region. By late March, it became apparent that flooding risks outweighed further benefits of the seeding program for the season. Although the higher elevation SNOTEL sites that were established by the Division of Water Resources for program suspension criteria in this area were still a bit below their pre-defined suspension thresholds, it was observed that lower elevation snowpack was reaching unprecedented highs. Given this, the seeding program was suspended and ended for the season a week early on March 24. Figure 4.8 shows the regional March precipitation as a percentage of normal.

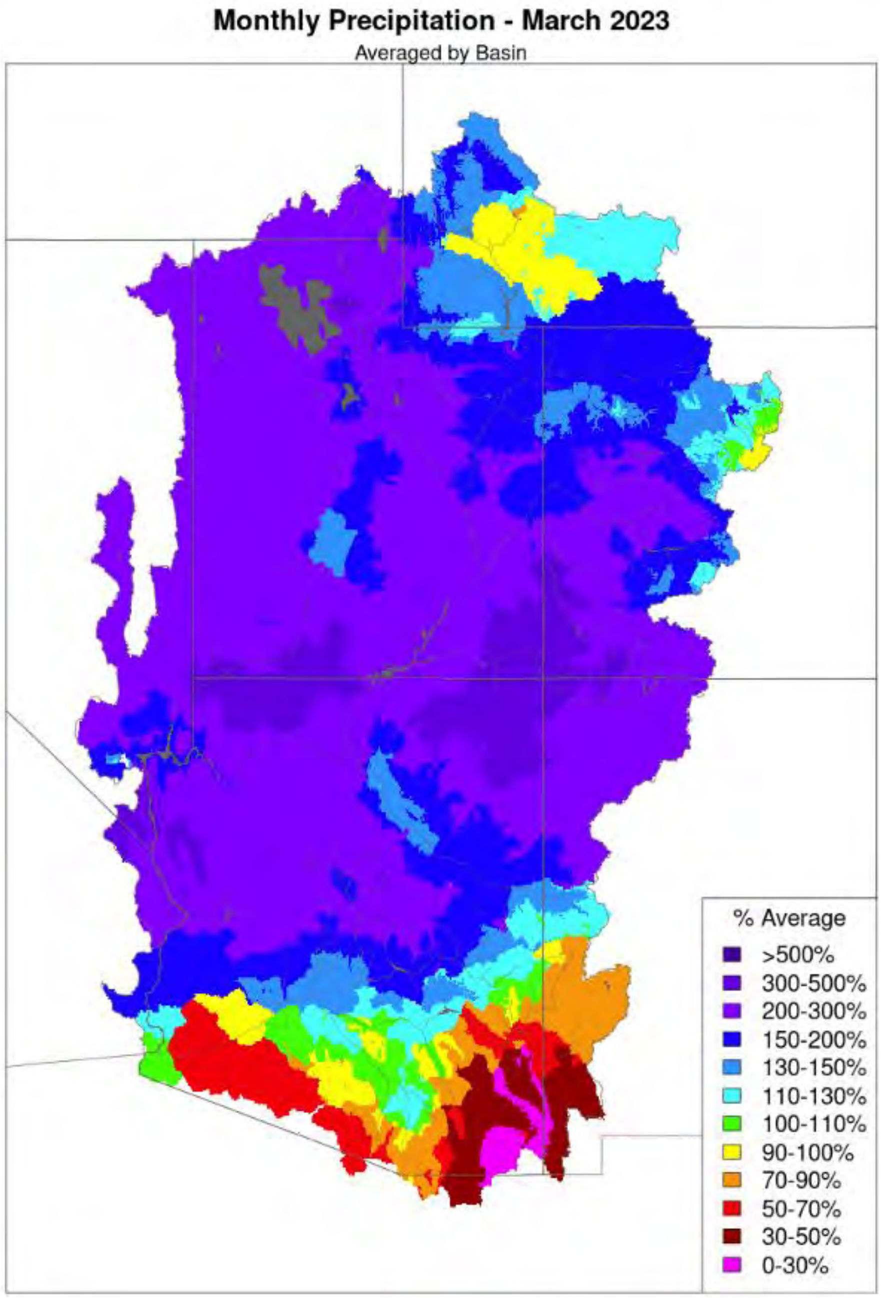


Figure 4.8 **March 2023 precipitation, percent of normal**

A deep longwave began to develop just off the coast of the Pacific Northwest on the 4th of March which put Utah under the influence of southwesterly flow pattern. One of several shortwave troughs rotating around this main low, ejected northeastward and across Utah during the afternoon and evening hours. Increasing mid-level moisture within the southwesterly flow pattern coupled with low-level warm advection and allowed snow to develop across the program area around midday, which then increased through the evening hours of the 4th as the wave and an associated cold front at 700mb tracked eastward and through Utah. The frontal boundary was accompanied by a band of convective snow, an abrupt wind shift from southwesterly to westerly, and significant drop in temperatures. Snow decreased in intensity once the front pushed just south of the program area after midnight on the 5th, but lingering moisture in the cold westerly flow pattern kept snow showers lingering up until 0900 MST on the 5th. Storm total SWE was in the 0.4-0.6” range.

A broad longwave trough continued to remain centered just off the coast of the Pacific Northwest on March 5th with additional shortwave troughs rotating around the large feature. Utah remained on the downstream side of this deep low with the flow staying westerly to southwesterly in direction. One of the shortwave troughs crossed Utah on the evening of the 4th into the morning of the 5th and pushed a cold frontal boundary southward across the state. This front stalled over central Utah by 0900 MST on the 5th with conditions further north and over the program area drying out through the afternoon hours. The dry break was brief as another embedded trough ejected away from the main low and moved through Utah on the evening of the 5th into the morning of the 6th. This forced the stalled boundary back northward and over the program area which brought another round of moderate to heavy snow within a westerly flow regime. As a result, several CNG sites were activated on the evening of the 5th and ran overnight into the morning hours of the 6th before ending. Total snow water equivalent (SWE) for this event ranged from 0.6-0.9”.

A long wave trough pattern remained engulfed over the Pacific Northwest on the 8th with several shortwaves rotating around the main low. Weak warm advection developed over northern Utah on the morning of the 8th and caused light snowfall to develop over the area which continued into the afternoon hours. Snow showers began to increase during the early evening hours of the 8th as an upper-level trough and its associated frontal zone approached the area from the northwest. CNG sites were activated around 1400 MST and ran late into the evening of the 8th. Dry and very cold air started to settle in across the area during after midnight on the 9th which brought an end to snow shower activity as well as seeding operations. Total snow water equivalent (SWE) for this event ranged from 0.1-0.3”.

Weak warm advection on the morning of the 12th combined with lingering mid-level moisture, daytime heating and a very subtle shortwave trough to bring scattered snow shower activity to the program area during the afternoon hours. Seeding was initiated around 1200 MDT as numerous showers and thunderstorms developed over the Uintas and continued until showers diminished after 1800 MDT. Storm total SWE for this event was light and ranged between 0.1-0.3”.

A significant Atmospheric River combined with a frontal boundary and produced a band of heavy snowfall across northern Utah on the morning of the 15th which slowly sagged southward and across the rest of the state throughout the day. Mild southwesterly flow ahead of the front shifted northwesterly behind its passage and 700mb temperatures fell from near -2C in the morning to near -9C in the evening. Heavy precipitation also transitioned to more showery behind the frontal passage where scattered showers and thunderstorms lingeried up until drier air spread in and conditions dried out after 1800 MDT. Upwards of 1.0” of SWE was observed across the program area.

A large trough made its way onshore and into California on the evening of the 19th then pushed into far northwest Utah during the afternoon hours of the 20th. Deep lift and daytime heating ahead of this trough allowed scattered showers and thunderstorms to pop up over the terrain of northern Utah. Showers and storms continued over the region through the early evening hours before tapering off and ending after 2000 MDT as the trough pushed off to the east. Seeding was conducted to target these scattered showers from roughly 1200 MDT through 2000 MDT. All in all, the seeding area picked up around 0.1-0.3” of SWE.

A splitting upper-level trough made its way through Utah during the early morning hours on the 20th of March. The southern portion of the split system dug too far south to have an appreciable impact on the western Uinta target area. The northern section, however, pushed a weakening cold front southeast and across Utah on the 20th, with it crossing the program area between late morning and early afternoon. Strong, dry, and warm southwesterly flow ahead of the cold front quickly turned northwest following its passage where it caused 700mb temperatures to fall from -2°C down to -10°C in its wake. Precipitation was largely confined to right along and behind the front and only lasted for a few hours before conditions dried out early in the evening. Seeding operations were activated right as the front was pushing across the area and ceased early in the evening as conditions dried out. Around 0.1-0.2” of SWE fell across the program area.

The last seeding event of the 2022-2023 season took place on March 22nd. It was the result of a broad and moist Pacific storm system that gradually slid eastward and forced a cold front into Utah during the afternoon hours. An area of moderate to heavy precipitation occurring within a southwesterly flow regime initially developed across the area early in the morning. As the cold front pushed in and crossed the area in the afternoon, ongoing precipitation turned showery and the flow aloft shifted from southwesterly to northwesterly. Some of the showers developed into weak thundershowers during the afternoon hours, which can be favorable for cloud seeding. As a result, seeding operations were activated early in the afternoon and ran until conditions began to dry out early in the evening. Total SWE was limited with this system and only amounted to around 0.2-0.4”.

5. ASSESSMENT 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, among all cloud seeding project types, the most consistent results have been observed in wintertime seeding programs in mountainous areas, with results indicating 5-15 percent increases in seasonal precipitation. Establishing an accurate approximation of the effects of seeding within a single operational season can be challenging. Historically a rigorous study of seeding increase estimates required a multi-year randomized seeding evaluation. This multi-year assessment method made it impossible to address financial concerns in real time and encumbered projects with substantial operational limitations.

To provide our clients with greater decisioning power, we developed a mathematical evaluation process that enables us to perform single and multiple season evaluations. This model is based on a "target and control" comparison of a given variable that is affected by seeding (precipitation or snowpack) between a "target" area (where seeding occurred for the season being assessed) and a "control" area (where no seeding occurred for the season being assessed)

After identifying appropriate control sites, data for the selected variable (e.g., precipitation) is analyzed for both the "target" area and the "control" area **for years where no seeding was performed in either area**. A mathematical model (regression) is developed to determine the relationship between precipitation in the "target" area and precipitation in the "control" area under natural circumstances. This mathematical model is then used to analyze the selected variable in years where seeding **did not** occur in the "control" area but **did** occur in the "target" area. Using this model with data for the control sites, a reasonable prediction can be made of what would have transpired in the target area had no seeding occurred, then compare this to what actually happened in the target area. Consistent differences between the predicted and observed target area data may be attributed to cloud seeding effects, although with a low level of confidence until sufficient seeded season data is accumulated.

This target and control technique works well where good mathematical correlation can be found between target and control area precipitation. Generally, the closer the two areas are geographically, and the more similar they are in terms of elevation and topography, the higher the correlation and the more certain the results. Areas selected that are too close together, however, can be subject to contamination of the control sites by seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, a correlation coefficient (r) of 0.90 or better would be considered excellent, and correlations around 0.85 would be very good. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set is explained by the regression equation used to estimate the subject variable (expected precipitation or snowpack) in the seeded years. Correlations less than about 0.80 are still acceptable, but it would likely take much longer to attach any statistical significance to the apparent results of seeding.

5.2 Considerations in the Development of Target/Control Evaluations

With the advent 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 take necessary measurements. This is still done at some sites although most have been automated. Historically, Utah has had snowpack measurements taken at (usually) monthly intervals. Precipitation and snowpack data used in the analysis were obtained from the NRCS and/or from the National Climatic Data Center. The current season NRCS data are considered provisional and subject to quality control analysis by the NRCS.

There have been, and continue to be, multiple cloud seeding programs conducted in the State of Utah. Consequently, 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 SNOTEL measurement sites in Utah have likely been affected at some time by numerous historical and current seeding programs.

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. The inclusion of control sites at somewhat varying latitudes (north-south), helping to bracket the target area, may improve the estimation of natural target area precipitation under variable upper airflow patterns.

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 if the data significantly diverges over time from other sites in the area. SNOTEL sites, the type used in the evaluation of the Western Uintas program, typically have reliable long-term records with external variables (such as terrain aspect and surrounding vegetation) carefully selected or maintained.

5.3 Evaluation of Snow Water Content

Historically, the Soil Conservation Service (SCS) routinely measured the mountain snowpack at snow courses once or twice per month, usually starting in January and continuing until May or June. Measurements were made by visiting the snow course (commonly a group of ten measurement points) and taking core samples of the snow to determine the water content and depth of the snow at each designated location along the course. Though this manual method is still being used at some sites, beginning in the 1980s, the NRCS (formerly the SCS) automated SNOTEL system has provided daily measurements of snow water (and precipitation) at many of the mountain sites. With the use of a snow pillow, the water equivalent of the snowpack can be determined remotely by reading the weight of the snow on the snow pillow. The water content within the snowpack is important since, after consideration of antecedent soil moisture conditions, it ultimately determines how much water will be available as runoff when the snow melt occurs. Hydrologists routinely use snow water content to make forecasts of streamflow during the spring and early summer months. As with the precipitation storage gauge and SNOTEL precipitation gauge networks, Utah also has access to an excellent snow course and SNOTEL snow pillow reporting system via the NRCS. Many of the same reporting mountain sites are configured with collocated precipitation and snowpack measurements. Consequently, it was judged important to evaluate the effects of seeding on snowpack as well.

There are some potential pitfalls with snowpack measurements that must be recognized when using snow water content to evaluate seeding effectiveness. One problem that can occur is that not all winter storms are cold, and sometimes rain as well as snow falls in the mountains. This can lead to a disparity between precipitation totals (which measure everything that falls) and snowpack water content (which measures only the water held in the snowpack at a particular time). Also, warm periods can occur between snowstorms particularly in the spring season. If a significant warm period occurs, some of the precipitation that fell as snow may melt or sublimate by the time the next snow course measurement is made. This can also lead to a greater disparity between snow water content and precipitation at lower elevations (where more snow will melt in warm weather) than at higher elevations.

Another factor that can have an effect on the indicated results of the snowpack evaluation is the date on which the snowpack measurement was made. These measurements are generally made near the end of the month at the snow course sites and, since the advent of SNOTEL, are now made daily where possible. Prior to SNOTEL, and at those sites where snow courses are still measured by visiting the site, the measurement is recorded on the day it was made. In some cases, because of scheduling issues or stormy weather, the manual snow course measurements may have been made as much as several days before or after the end of the month. This can lead to a disparity in the snowpack water content readings when comparing one group (such as a control) with another control or target group. Normally, however, snowpack measurements are made within a few days of the intended date.

April 1st snowpack readings are widely used for runoff forecasting since they usually closely represent the maximum snow accumulation for the winter season. Most streamflow and reservoir storage forecasts are made on the basis of the April 1st snowpack data. For that reason, and because three to four months of seeding are generally represented in the April 1st snowpack measurements, April 1st was selected as the date for our snowpack analyses.

Target/Control Sites and Regression Equation Development

The procedure was essentially the same as what was done for the precipitation evaluation, e.g., control and target area sites were selected, and average values for each were determined. Seven target area snow measurement sites were utilized for the Western Uintas Program, as shown in Figure 5.1. Table 5-1 provides the target area site names, elevations, and locations of these sites. The average elevation of the target sites is 8,637 feet MSL.

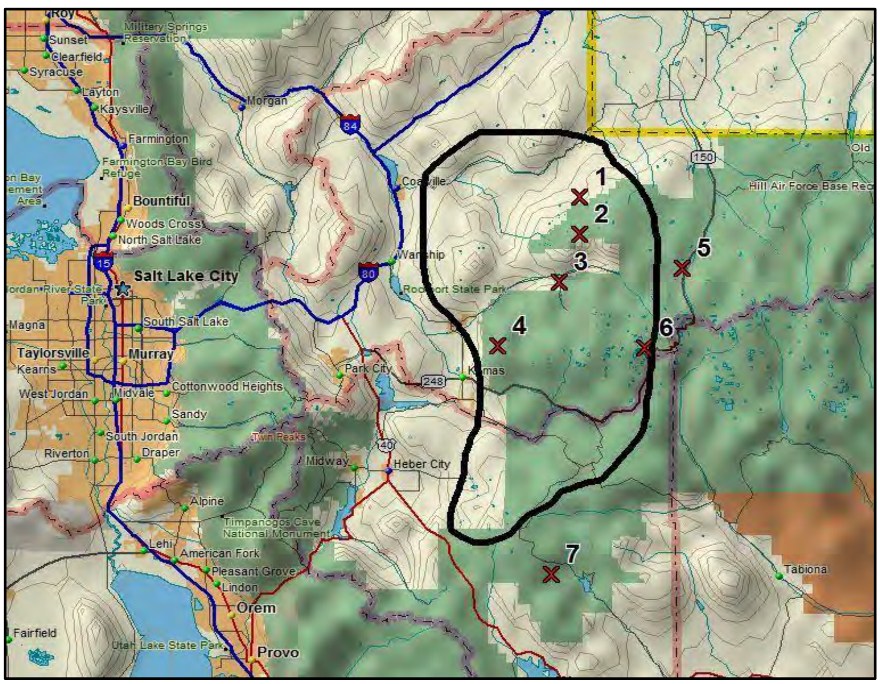


Figure 5.1 **Western Uintas target area and snowpack target sites**

Table 5-1
Target area snowpack sites

Map Label	Site Name	Elev. (Ft)	Lat. (N)	Long. (W)
1	Chalk Creek #2	8,200	40° 54'	111° 04'
2	Chalk Creek #1	9,100	40° 51'	111° 04'
3	Smith & Morehouse	7,600	40° 47'	111° 06'
4	Redden Mine, Lower	8,500	40° 41'	111° 13'
5	Hayden Fork	9,100	40° 48'	110° 53'
6	Trial Lake	9,960	40° 41'	110° 57'
7	Currant Creek	8,000	40° 21’	111° 05’

The five control sites are located in southern Idaho, northeastern Nevada and central Utah as shown in Figure 5.2. Control area site names, elevations and locations are provided in Table 5-2. The elevations of the control area sites average 6,887 feet (MSL). The non-seeded seasons were 1970-1988 and 1997-2000 (a total of 23 seasons). **Many more historical seasons were available for the snow water content analyses than for precipitation data, 23 versus 11 seasons. As a consequence, the snow water content analyses results are likely to be much more reliable than the precipitation analyses for this particular seeding program, and are the focus of this evaluation section.**

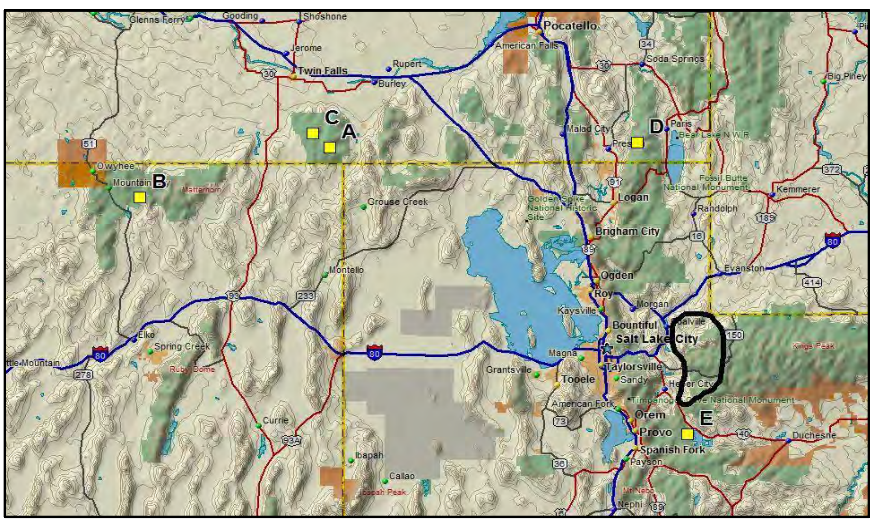


Figure 5.2 Western Uintas target area and snow control sites (squares)

Table 5-2
Control area snowpack sites

Map Label	Site Name	Site ID	Elev. (Ft)	Lat. (N)	Long. (W)
A	Badger Gulch SC, ID	14G03	6,660	42°06'	114°10'
B	Big Bend, NV	15H04S	6,700	41°46'	115°43'
C	Magic Mountain, ID	14G02S	6,880	42°11'	114°18'
D	Willow Flat SC, ID	11G04	6,070	42°08'	111°38'
E	Strawberry Divide, UT	11J08S	8,123	40°11'	111°13'

The linear regression equation developed from the historical relationship between the average control snowpack data and the average target snowpack data for April 1st was the following:

$Y_C = 0.741 (X_O) + 6.36$ (4)

where Y_C is the calculated average snow water content (inches) for the seven-station target and X_O is the five-station control average observed snow water content for April 1st.

Linear Regression Snowpack Analysis

When the observed average control snow water content (22.90 inches) for April 1st, 2023 period was inserted in equation (1), the most probable average target area snow water content was calculated to be 23.33 inches. The actual observed average precipitation for the target group was 27.00 inches. This yields a single-season ratio of 1.16, which (for this single season) is itself not indicative of a seeding effect. As stated before, the single-season evaluation results carry very little statistical significance. The strength of the evaluation lies in the multi-year results as shown below.

The combined (26-year) snow water linear regression evaluation for April 1st, for the Western Uintas target sites, yields a ratio of 1.03. This long-term mean excludes water years 2004 and 2015 during which abnormal early snowmelt occurred, and thus includes 26 seeded seasons. The implied 3% increase based on the snowpack evaluation is equivalent to an average of about 0.53 inches more water over the watersheds than might have occurred without the cloud seeding. The snowpack evaluation for the seeded water years is summarized in Table 5-3.

Table 5-3
Summary of April 1st snow water content evaluation, using the Linear Regression technique.

Water Year	Control Average	Target Observed	Target Predicted	Obs/Pred Ratio	Excess Water (inches)
1989	17.22	18.04	19.12	0.94	-1.08
1990	6.94	14.79	11.50	1.29	3.28
1991	10.34	15.00	14.02	1.07	0.98
1992	3.44	10.29	8.91	1.15	1.38
1993	16.02	21.34	18.23	1.17	3.11
1995	11.96	18.43	15.22	1.21	3.21
2001	6.62	10.53	11.27	0.93	-0.74
2002	14.86	14.21	17.37	0.82	-3.16
2003	7.04	12.31	11.58	1.06	0.74
2005	14.26	21.09	16.93	1.25	4.16
2006	21.12	21.81	22.01	0.99	-0.20
2007	7.12	10.16	11.64	0.87	-1.48
2008	17.28	20.07	19.16	1.05	0.91
2009	14.06	17.17	16.78	1.02	0.39
2010	11.22	11.84	14.67	0.81	-2.83
2011	20.06	24.50	21.22	1.15	3.28
2013	9.14	10.69	13.13	0.81	-2.45
2014	11.16	16.61	14.63	1.14	1.98
2016	14.74	14.71	17.28	0.85	-2.57
2017	16.68	23.46	18.72	1.25	4.74
2018	7.40	10.29	11.84	0.87	-1.56
2019	18.44	21.64	20.02	1.08	1.62
2020	14.78	16.80	17.31	0.97	-0.51
2021	11.54	12.30	14.91	0.82	-2.61
2022	8.36	12.20	12.55	0.97	-0.35
2023	22.90	27.00	23.33	1.16	3.67
26 years	**12.87**	**16.43**	**15.90**	**1.033**	**0.53**

Multiple Linear Regression Snowpack Analysis

A multiple linear regression analysis has been conducted for snowpack, and exhibits much lower seasonal variability in the indicated observed/predicted ratios than does the corresponding linear regression. The r value is also much better than for the standard linear regression (0.90 vs. 0.79). This implies less background noise in this equation, and thus likely more reliable estimates of the true seeding effects. The results of the multiple regression snowpack analyses are provided in Table 5-4, implying about a 6% increase over the long term (obtained from the ratio of 1.06 shown in bold in the bottom row of that table). In the case of the Western Uintas evaluations, the multiple linear snowpack analysis is by far the strongest mathematically and is likely the most reliable for evaluation of this program.

A double ratio analysis using snowpack data (similar to that for precipitation) resulted in a ratio of 1.13, implying a 13% increase in the target area (relative to the control) during the seeded seasons. However, this result is a high outlier in these evaluations and may not be representative of the actual seeding effects. NAWC's best estimate of seeding effects for the Western Uintas program is about a 6% increase, as obtained in the multiple linear regression snowpack analysis.

Table 5-4
Summary of snow water content evaluation using the multiple linear regression technique.

Water Year	Magic Mtn, ID	Badger Gulch, ID	Willow Flat, ID	Big Bend, NV	Straw berry Div,	Target Observ ed	Est Target Snow	Obs/Pr ed Ratio	Excess Water (inches
1989	23.60	16.20	18.00	10.50	17.80	18.04	17.84	1.01	0.20
1990	10.20	7.70	4.00	0.00	12.80	14.79	13.45	1.10	1.34
1991	14.70	7.50	11.20	2.40	15.90	15.00	14.95	1.00	0.05
1992	3.60	3.00	3.70	0.00	6.90	10.29	9.05	1.14	1.24
1993	18.10	14.60	17.70	8.40	21.30	21.34	20.18	1.06	1.16
1995	15.70	10.40	12.90	3.90	16.90	18.43	16.52	1.12	1.91
2001	11.40	6.10	5.10	2.00	8.50	10.53	10.02	1.05	0.51
2002	20.90	15.80	14.30	10.40	12.90	14.21	14.88	0.96	-0.66
2003	10.60	4.20	8.10	2.00	10.30	12.31	10.71	1.15	1.61
2005	16.70	9.80	14.90	7.70	22.20	21.09	18.68	1.13	2.40
2006	28.20	18.20	21.00	14.50	23.70	21.81	21.03	1.04	0.78
2007	14.00	5.20	6.00	1.80	8.60	10.16	9.51	1.07	0.65
2008	20.00	16.80	19.00	11.60	19.00	20.07	19.16	1.05	0.91
2009	20.40	10.20	15.50	10.10	14.10	17.17	13.50	1.27	3.67
2010	15.70	11.20	10.80	8.40	10.00	11.84	11.97	0.99	-0.13
2011	21.80	15.40	24.60	13.80	24.70	24.50	21.82	1.12	2.68
2013	15.20	9.60	9.40	2.00	9.50	10.69	12.03	0.89	-1.34
2014	17.70	11.40	10.20	2.20	14.30	16.61	15.18	1.09	1.43
2016	22.40	14.70	14.80	9.50	12.30	14.71	14.11	1.04	0.61
2017	19.80	15.10	15.20	10.10	23.20	23.46	20.64	1.14	2.82
2018	12.70	6.90	7.10	2.70	7.60	10.29	9.79	1.05	0.49
2019	21.20	17.70	19.00	10.40	23.90	21.64	22.32	0.97	-0.67
2020	21.40	15.60	13.00	8.40	15.50	16.80	16.37	1.03	0.43
2021	16.60	12.40	12.00	6.70	10.00	12.30	12.78	0.96	-0.48
2022	14.90	7.00	7.00	2.00	10.90	12.20	11.50	1.06	0.70
2023	28.40	20.60	27.20	14.70	23.60	27.00	22.64	1.19	4.36
26 yrs	**17.53**	**11.67**	**13.14**	**6.78**	**15.25**	**16.43**	**15.41**	**1.066**	**1.02**

5.4 Summary of Evaluation Results

The April 1st **snowpack** analyses for 26 seeded seasons (2004 and 2015 were excluded) yield observed/predicted ratios of 1.03 (linear) and 1.06 (multiple linear). The results using April 1st snowpack imply average increases of roughly 3%-6%, which seems reasonable for this program, particularly in comparison to results of similar programs in the western U.S. and nearby programs in Utah. The April 1st snowpack evaluations are considered much more representative than the December-March precipitation evaluation (previously included in this section) due to a much longer historical period being available for the snow water versus precipitation evaluation of 23 versus 11 seasons, and a stronger statistical correlation (i.e., r value of 0.90). Also, of interest in the case of the snowpack evaluations is the much lower year-to-year variability observed in the results of the snowpack multiple linear evaluation, suggesting that this particular equation is likely the best predictor of the “expected” natural target area precipitation based on the available control site snowpack data. **This suggests a likely long-term average seeding effect in the neighborhood of 6% for this program.**

NAWC considers the Western Uintas evaluations to be conservative estimates of the effects of seeding for a variety of reasons. For example, some months that were included in the “seeded” period actually were not seeded during all seasons. Also, one of the control sites (Strawberry Divide) is located in an area that has been seeded for another program during some winter seasons. The snowpack evaluations are also conservative because they are based upon April 1st data. These data contain periods in the fall and early winter in which snowpack accumulated in the target area without any effects of seeding. This would dilute the indicated effects of seeding over the long term.

Due in large part to the continually rising demand for water across the Rocky Mountain States, there are no longer any particularly good control sites. The few potential sites that reside close to the target area and have adequate historic records are all likely affected by other nearby cloud-seeding projects each winter, thus reducing the apparent gains derived from cloud seeding

Another potential confounding issue in evaluating the effects of cloud seeding in the Western Uintas target area is that the historical target/control evaluations seem to be impacted by urban air pollution, based upon an analysis performed and published by NAWC (Griffith et al., 2005). A copy of the paper on this topic was provided in the 2005 report and is also available on NAWC’s website (www.nawcinc.com/nawcpapers.html). **That analysis documented an approximate 16% decline in the November through March precipitation at Trial Lake during the period from 1956 to 2004.** Data more recent than this would be affected by cloud seeding as well, with the competing effects difficult to separate.

The control area sites in northeastern Nevada and southwestern Idaho are primarily in unpopulated areas which would not be expected to be subject to the air pollution problems as discussed in the 2005 paper. On the other hand, from our investigations (Griffith et al., 2005) it appears that some of the target sites for the Western Uintas program are being negatively impacted by air pollution. The likely result then is that the equations used to evaluate the program may be over-predicting the amount of “natural” precipitation (i.e., that which would occur without seeding) in the target area during the seeded periods. As a consequence, the evaluations of the program are likely indicating less of a seeding effect than is actually occurring.

This situation was also considered in a study conducted by Givati and Rosenfeld (2004); they reported on an operational cloud seeding program being conducted in Israel, plus some areas in California that are exhibiting these pollution impacts. A quote from the Givati and Rosenfeld study is as follows: “In this study, we avoided addressing the possible confounding effects of the glaciogenic cloud seeding of the orographic clouds in both Israel and California. If seeding did enhance precipitation, the effects in the absence of seeding may have been larger than indicated in this study.” **In other words, cloud seeding may**

potentially be offsetting the negative effects of air pollution on precipitation. For example, if air pollution was reducing December through March precipitation by 10% and cloud seeding was increasing precipitation by 10%, the evaluations that we have been conducting for the Western Uintas may indicate no effect even though there actually was a 10% increase due to cloud seeding. And the corollary is that without cloud seeding, the drop in precipitation due to pollution effects might be more pronounced.

Appendix C contains additional information on the historical and seeded years precipitation and snow water averages, regression equations and predicted and observed values.

6. CONCLUSIONS

The difficulties involved in predicting seasonal increases in snowpack resulting from cloud seeding have been thoroughly described in this report. With those realities and their potential impacts summarized, we offer the following statements regarding the seeding project effectiveness.

The cumulative evaluation results using the regular and multiple linear regression techniques based on April 1st snow water content, indicate an estimated 3% to 6% seasonal average increase. These are considered to be the best, most credible (although perhaps still conservative) estimations of the true effects of the seeding program.

For the Western Uintas program, a 5% average increase would yield approximately ~0.8 inches of additional water over the target area. The target area comprises approximately 600 square miles. An average 0.8 inches of augmented water across the target would yield approximately ~25,000 additional acre-feet of runoff. Using an estimated average current cost of conducting the seeding program, the cost of producing the additional runoff via cloud seeding is approximately $3.50 per acre-foot.

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APPENDIX A SUSPENSION CRITERIA

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

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

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

1. Excess Snowpack Accumulation

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

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, South Eastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. The Weber-Ogden and Provo River – Utah Lake – Jordan River criteria apply to suspension considerations for the Western Uintas project. Since SNOTEL observations are available on a daily basis, suspensions (and cancellation of suspensions) can be made on a daily basis using linear interpolation of the first of month criteria. For the Western Uintas, four SNOTEL sites (Chalk Creek #1, Trial Lake, Smith and Morehouse, and Rock Creek) have date-specific snow water equivalent criteria on which suspension decisions can be based.

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

2. Rain-induced Winter Floods

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

3. Severe Weather

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

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

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

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

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

APPENDIX B SEEDING OPERATIONS TABLES

Table B-1
Generator Hours – Western Uintas, 2022-2023
Storms 1-11 (rounded to quarter hour)

Storm	1	2	3	4	5	6	7	8	9	10	11
Date	Dec 12-13	Dec 15	Dec 21	Dec 27-28	Dec 31	Jan 6	Jan 10-11	Jan 15	Jan 17-18	Jan 27-28	Feb 5
SITE											
WU-2		9		10							
WU-3	20.75	9		10							
WU-4									17.25		
WU-5	29	11		22		11	14.75	8.5			7
WU-6	27	9	9			9	18	8		20.75	5
WU-7	27	9	9	22		3	18	8		20.75	7
WU-8	28.5	9	9	20			18	8		20.75	6
WU-9	38	9	10.5	11			18	8		20.75	7
WU-10							19	8		19	
WU-11	27		8.5	22	6.75		15	7			6.5
WU-12	27.5		8.5	22	6.75		18	7			6.75
Storm Total	224.75	65	54.5	139	13.5	23	138.75	62.5	17.25	102	42.25

Table B-2
Generator Hours – Western Uintas, 2021-2022
Storms 12-22 (rounded to quarter hour)

Storm	12	13	14	15	16	17	18	19	20	21	22
Date	Feb 6	Feb 8	Feb 21	Feb 27-28	Mar 4-5	Mar 5-6	Mar 8	Mar 12	Mar 15	Mar 20	Mar 22
SITE											
WU-2	3.75	5									
WU-3	3.75	5									
WU-4	6.5	5									
WU-5			5	14	15	10		5	10		
WU-6		5	6.5	14		12					
WU-7		5	7	12			4	5			
WU-8		5	5	12	13		4	5			
WU-9			6.25	14	15	14	5	5	9	8	
WU-10				14	13	14	5	5		8	
WU-11			6.5	12		12	5		9	8	6
WU-12			7	10.5		14	5		9	8	7.75
Storm Total	13	30	43.25	102.5	56	76	18	25	37	32	15.75

APPENDIX C EVALUATION DATA

Western Uintas December – March Precipitation, Linear Regression

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:					
1982	21.23	20.44	17.78	1.15	2.66
1983	16.45	13.03	14.56	0.90	-1.53
1984	20.43	13.81	17.24	0.80	-3.42
1985	9.63	11.47	9.95	1.15	1.52
1986	18.55	17.23	15.97	1.08	1.26
1987	8.73	8.41	9.34	0.90	-0.93
1988	10.88	10.77	10.79	1.00	-0.02
1997	20.68	17.74	17.41	1.02	0.34
1998	16.48	14.34	14.57	0.98	-0.23
1999	14.28	12.64	13.09	0.97	-0.45
2000	15.15	14.47	13.68	1.06	0.79
Mean	**15.68**	**14.03**	**14.04**	**1.00**	**0.00**

Seeded period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1989	15.03	13.37	13.60	0.98	-0.23
1990	9.85	11.59	10.10	1.15	1.48
1991	10.00	11.46	10.20	1.12	1.25
1992	5.15	6.01	6.93	0.87	-0.92
1993	17.13	17.83	15.01	1.19	2.82
1994*	9.15	10.71	9.63	1.11	1.08
1995	12.45	14.71	11.86	1.24	2.86
1996*	18.73	18.37	16.09	1.14	2.28
2001	9.23	8.64	9.68	0.89	-1.04
2002	13.45	10.37	12.53	0.83	-2.16
2003	9.93	9.61	10.15	0.95	-0.54
2004	14.58	10.36	13.29	0.78	-2.93
2005	11.60	14.99	11.28	1.33	3.70
2006**	21.43	16.99	17.91	0.95	-0.93
2007**	12.23	9.29	11.71	0.79	-2.42
2008**	16.93	16.54	14.88	1.11	1.67
2009**	16.20	14.67	14.39	1.02	0.28
2010**	12.13	9.41	11.64	0.81	-2.22
2011**	17.43	17.91	15.21	1.18	2.70
2012*	11.78	8.47	11.40	0.74	-2.93
2013	13.35	9.03	12.46	0.72	-3.44
2014	14.48	13.20	13.22	1.00	-0.02
2015	11.08	7.99	10.93	0.73	-2.94
2016	17.80	13.16	15.47	0.85	-2.31
2017	21.30	23.00	17.83	1.29	5.17
2018	11.63	8.80	11.30	0.78	-2.50
2019	15.33	14.97	13.80	1.09	1.17
2020	15.20	12.60	13.71	0.92	-1.11
2021	11.73	9.77	11.37	0.86	-1.60
2022	12.00	11.11	11.55	0.96	-0.44

2023	16.50	20.36	14.59	1.40	5.77
Mean	**13.75**	**12.78**	**12.38**	**1.03**	**0.40**

* No seeding in target areas
** Seeding in Weber Basin but not in Provo R Basin, these are still included in the mean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.877723**
R Square	**0.770398**
Adjusted R Square	0.744887
Standard Error	1.728461
Observations	11

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	**3.456066**	1.994168	1.733087	0.117116	-1.05506
X Variable 1	**0.674813**	0.122798	5.495294	0.000383	0.397024

Western Uintas April 1 Snowpack, Linear Regression

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
Non-seeded Years					
1970	16.14	16.21	18.32	0.89	-2.11
1971	18.66	21.43	20.19	1.06	1.24
1972	19.18	18.17	20.57	0.88	-2.40
1973	16.02	16.61	18.23	0.91	-1.62
1974	18.42	16.77	20.01	0.84	-3.24
1975	20.08	19.97	21.24	0.94	-1.27
1976	17.46	17.33	19.30	0.90	-1.97
1977	6.24	8.97	10.98	0.82	-2.01
1978	16.18	19.23	18.35	1.05	0.88
1979	17.40	17.80	19.25	0.92	-1.45
1980	19.86	25.26	21.08	1.20	4.18
1981	8.38	12.66	12.57	1.01	0.09
1982	21.08	23.50	21.98	1.07	1.52
1983	18.42	20.90	20.01	1.04	0.89
1984	24.80	22.01	24.74	0.89	-2.72
1985	16.06	21.44	18.26	1.17	3.18
1986	15.84	25.73	18.10	1.42	7.63
1987	8.08	13.97	12.35	1.13	1.62
1988	11.42	14.23	14.82	0.96	-0.59
1997	19.72	22.41	20.97	1.07	1.44
1998	14.30	16.39	16.96	0.97	-0.57
1999	13.34	14.86	16.24	0.91	-1.39
2000	13.90	15.41	16.66	0.93	-1.25

Mean	16.13	18.32	18.31	1.00	0.00

Seeded Period

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1989	17.22	18.04	19.12	0.94	-1.08
1990	6.94	14.79	11.50	1.29	3.28
1991	10.34	15.00	14.02	1.07	0.98
1992	3.44	10.29	8.91	1.15	1.38
1993	16.02	21.34	18.23	1.17	3.11
1994*	8.42	13.31	12.60	1.06	0.72
1995	11.96	18.43	15.22	1.21	3.21
1996*	16.96	22.21	18.93	1.17	3.29
2001	6.62	10.53	11.27	0.93	-0.74
2002	14.86	14.21	17.37	0.82	-3.16
2003	7.04	12.31	11.58	1.06	0.74
2004***	11.74	9.83	15.06	0.65	-5.23
2005	14.26	21.09	16.93	1.25	4.16
2006**	21.12	21.81	22.01	0.99	-0.20
2007**	7.12	10.16	11.64	0.87	-1.48
2008**	17.28	20.07	19.16	1.05	0.91
2009**	14.06	17.17	16.78	1.02	0.39
2010**	11.22	11.84	14.67	0.81	-2.83
2011**	20.06	24.50	21.22	1.15	3.28
2012*	9.22	8.86	13.19	0.67	-4.33
2013	9.14	10.69	13.13	0.81	-2.45
2014	11.16	16.61	14.63	1.14	1.98
2015***	4.66	6.40	9.81	0.65	-3.41
2016	14.74	14.71	17.28	0.85	-2.57
2017	16.68	23.23	18.72	1.24	4.51
2018	7.40	10.29	11.84	0.87	-1.56
2019	18.44	21.64	20.02	1.08	1.62
2020	14.78	16.80	17.31	0.97	-0.51
2021	11.54	12.30	14.91	0.82	-2.61
2022	8.36	12.20	12.55	0.97	-0.35
2023	22.90	27.00	23.33	1.16	3.67
Mean	12.87	16.43	15.90	**1.033**	**0.53**

* No seeding in target areas
** Seeding in Weber Basin only, not in Provo R Basin but still included
*** Excluded due to excessive snow melt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.790698001**
R Square	**0.625203329**
Adjusted R Square	0.607355868

Standard Error	2.604867978
Observations	23

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	6.361749358	2.091542482	3.041654383	0.006201346	2.012147901
X Variable 1	0.741148292	0.125222591	5.918646823	7.10871E-06	0.480733612

Western Uintas April 1 Snowpack, Multiple Linear Regression

YEAR	Magic Mtn, ID	Badger Gulch, ID	Willow Flat, ID	Big Bend, NV	Strawberry Divide, UT	YOBS	YCALC	RATIO	EXCESS
Non-Seeded Years									
1970	23.30	15.30	13.10	10.80	18.20	16.21	17.11	0.95	-0.89
1971	24.80	14.10	20.40	12.70	21.30	21.43	18.69	1.15	2.74
1972	33.40	20.40	13.20	10.90	18.00	18.17	17.76	1.02	0.41
1973	21.60	14.40	15.40	8.90	19.80	16.61	18.45	0.90	-1.83
1974	25.20	20.00	17.00	11.90	18.00	16.77	18.95	0.88	-2.18
1975	24.40	18.70	20.40	15.70	21.20	19.97	20.06	1.00	-0.09
1976	22.00	15.50	21.20	12.70	15.90	17.33	16.71	1.04	0.62
1977	8.40	6.00	6.00	3.10	7.70	8.97	9.84	0.91	-0.87
1978	19.20	12.40	15.20	9.20	24.90	19.23	20.71	0.93	-1.48
1979	19.60	14.60	19.40	10.10	23.30	17.80	21.02	0.85	-3.22
1980	21.50	15.70	20.40	13.70	28.00	25.26	23.35	1.08	1.91
1981	12.00	7.20	6.60	2.00	14.10	12.66	13.70	0.92	-1.04
1982	28.10	18.20	19.30	13.70	26.10	23.50	22.32	1.05	1.18
1983	24.60	14.60	12.90	15.70	24.30	20.90	19.19	1.09	1.71
1984	32.00	19.50	25.10	18.00	29.40	22.01	24.14	0.91	-2.12
1985	20.80	14.70	15.40	9.10	20.30	21.44	18.92	1.13	2.52
1986	19.10	16.10	16.60	4.40	23.00	25.73	22.17	1.16	3.56
1987	10.60	8.80	6.90	2.30	11.80	13.97	13.24	1.06	0.73
1988	16.10	9.00	10.80	6.80	14.40	14.23	13.75	1.04	0.48
1997	26.90	18.60	17.40	8.40	27.30	22.41	23.99	0.93	-1.58
1998	18.20	11.50	16.00	7.20	18.60	16.39	17.39	0.94	-1.01
1999	20.00	13.80	13.40	8.00	11.50	14.86	13.69	1.08	1.16
2000	18.50	11.90	13.10	8.80	17.20	15.41	16.12	0.96	-0.71
Mean	21.32	14.39	15.44	9.74	19.75	18.32	18.32	1.00	0.00

Seeded Period

YEAR	Magic Mtn, ID	Badger Gulch, ID	Willow Flat, ID	Big Bend, NV	Strawberry Divide, UT	YOBS	YCALC	RATIO	EXCESS
1989	23.60	16.20	18.00	10.50	17.80	18.04	17.84	1.01	0.20
1990	10.20	7.70	4.00	0.00	12.80	14.79	13.45	1.10	1.34
1991	14.70	7.50	11.20	2.40	15.90	15.00	14.95	1.00	0.05
1992	3.60	3.00	3.70	0.00	6.90	10.29	9.05	1.14	1.24
1993	18.10	14.60	17.70	8.40	21.30	21.34	20.18	1.06	1.16
1994*	11.60	8.40	11.60	0.40	10.10	13.31	12.88	1.03	0.44
1995	15.70	10.40	12.90	3.90	16.90	18.43	16.52	1.12	1.91
1996*	21.20	14.70	16.30	10.20	22.40	22.21	19.96	1.11	2.25
2001	11.40	6.10	5.10	2.00	8.50	10.53	10.02	1.05	0.51
2002	20.90	15.80	14.30	10.40	12.90	14.21	14.88	0.96	-0.66
2003	10.60	4.20	8.10	2.00	10.30	12.31	10.71	1.15	1.61
2004***	20.20	13.00	11.40	3.60	10.50	9.83	13.30	0.74	-3.47
2005	16.70	9.80	14.90	7.70	22.20	21.09	18.68	1.13	2.40
2006**	28.20	18.20	21.00	14.50	23.70	21.81	21.03	1.04	0.78
2007**	14.00	5.20	6.00	1.80	8.60	10.16	9.51	1.07	0.65
2008**	20.00	16.80	19.00	11.60	19.00	20.07	19.16	1.05	0.91
2009**	20.40	10.20	15.50	10.10	14.10	17.17	13.50	1.27	3.67
2010**	15.70	11.20	10.80	8.40	10.00	11.84	11.97	0.99	-0.13
2011**	21.80	15.40	24.60	13.80	24.70	24.50	21.82	1.12	2.68
2012*	17.20	10.90	9.30	2.80	5.90	8.86	10.14	0.87	-1.29
2013	15.20	9.60	9.40	2.00	9.50	10.69	12.03	0.89	-1.34
2014	17.70	11.40	10.20	2.20	14.30	16.61	15.18	1.09	1.43
2015***	13.00	5.40	0.00	0.00	4.90	6.40	7.25	0.88	-0.85
2016	22.40	14.70	14.80	9.50	12.30	14.71	14.11	1.04	0.61
2017	19.80	15.10	15.20	10.10	23.20	23.23	20.64	1.13	2.59
2018	12.70	6.90	7.10	2.70	7.60	10.29	9.79	1.05	0.49
2019	21.20	17.70	19.00	10.40	23.90	21.64	22.32	0.97	-0.67
2020	21.40	15.60	13.00	8.40	15.50	16.80	16.37	1.03	0.43
2021	16.60	12.40	12.00	6.70	10.00	12.30	12.78	0.96	-0.48
2022	14.90	7.00	7.00	2.00	10.90	12.20	11.50	1.06	0.70
2023	28.40	20.60	27.20	14.70	23.60	27.00	22.64	1.19	4.36
Mean	**17.53**	**11.67**	**13.14**	**6.78**	**15.25**	**16.43**	**15.41**	**1.066**	**1.02**

* No seeding in target areas
** Seeding in Weber Basin only, not in Provo R Basin but still included
*** Excluded due to excessive snow melt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.90475791**

R Square	**0.8185 86875**
Adjusted R Square	0.7652 30074
Standard Error	2.0142 22267
Observations	23

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	**3.9957 42621**	1.84902 9881	2.1609 94077	0.0452 57773	0.0946 25126	7.8968 60115	0.0946 25126	7.8968 60115
Magic Mtn	**- 0.1306 4576**	0.21561 0564	- 0.6059 3394	0.5525 63859	- 0.5855 4492	0.3242 53403	- 0.5855 4492	0.3242 53403
Badger Gulch	**0.4109 87093**	0.30428 3703	1.3506 70735	0.1945 07174	- 0.2309 963	1.0529 70487	- 0.2309 963	1.0529 70487
Willow Flat	**0.1183 62921**	0.18066 398	0.6551 55063	0.5211 35389	- 0.2628 0529	0.4995 31132	- 0.2628 0529	0.4995 31132
Big Bend	**- 0.1709 8141**	0.20373 4461	- 0.8392 3655	0.4129 83076	- 0.6008 2415	0.2588 61333	- 0.6008 2415	0.2588 61333
Strawberry	**0.5583 59365**	0.11949 8786	4.6725 10759	0.0002 18598	0.3062 38612	0.8104 80118	0.3062 38612	0.8104 80118

APPENDIX D GLOSSARY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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