Annual Cloud Seeding Report
High Uintas Program
2022-2023 Winter Season

Prepared For:

Duchesne County Water Conservancy District

Uintah Water Conservancy District

State of Wyoming

Metropolitan Water District of Southern California

State of Utah, Division of Water Resources

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EXECUTIVE SUMMARY

The Duchesne County Water Conservancy District and the Uintah Water Conservancy District were joined by the Central Utah Water Conservancy District in supporting an operational seeding project, beginning in the 2002-2003 winter season. The intended target area of this program has been the southern slope of the Uinta Mountains above 8,000 feet. The High Uintas program currently utilizes 20 ground-based, manually operated Cloud Nuclei Generator (CNG) sites, burning a 2% Silver Iodide solution. Some sites established for the adjacent Western Uintas seeding program are also utilized to target the High Uintas. In addition, a remotely operated site located at Moon Lake has been added to the program. The goal of the seeding program is to augment wintertime snowpack/precipitation over the seeded watersheds. Cost sharing for the seeding program is provided by the Utah Division of Water Resources, with additional funds from the Lower Colorado River Basin States providing for an early-season extension to the seeding program.

Precipitation and snowfall were well above average during the 2022-2023 winter season. The Uintas region fared very well this season compared to many surrounding areas. As of April 1, 2023, SNOTEL observations for the Natural Resource Conservation Service showed snow water content averaging about 187% of normal (median) for the Duchesne Basin and about 163% of normal for sites in the portions of the Uinta Range that compose the Green River Basin. Water year precipitation percentages were 159% of the median for the Duchesne Basin and around 133% of normal for sites in the Green River Basin. The snowpack percentages remained much higher than precipitation percentages this season due to early season precipitation in October and November essentially falling as all snow.

A total of 1562.5 CNG hours were conducted during 31 storm periods for the core High Uintas program this season, out of a maximum budgeted 2,750 hours. An additional 258.5 hours of seeding were conducted (during 3 storm periods) in November for the Lower Basin States sponsored extension period. There were no seeding suspensions for the High Uintas program during the 2022-2023 season.

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

As summarized in Section 5 of the report, determination of the exact seeding effects in the High Uintas is particularly challenging for a variety of reasons**. Based on a review of nearly 2-decades worth of data, NAWC has estimated that the seeding program is generating approximately a 3-5% seasonal increase in seasonal snowpack for this program. This equates to an approximate program yield of 36,000 additional acre-feet of annual runoff as well as significant increases to ground water/aquifer recharge.**

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.

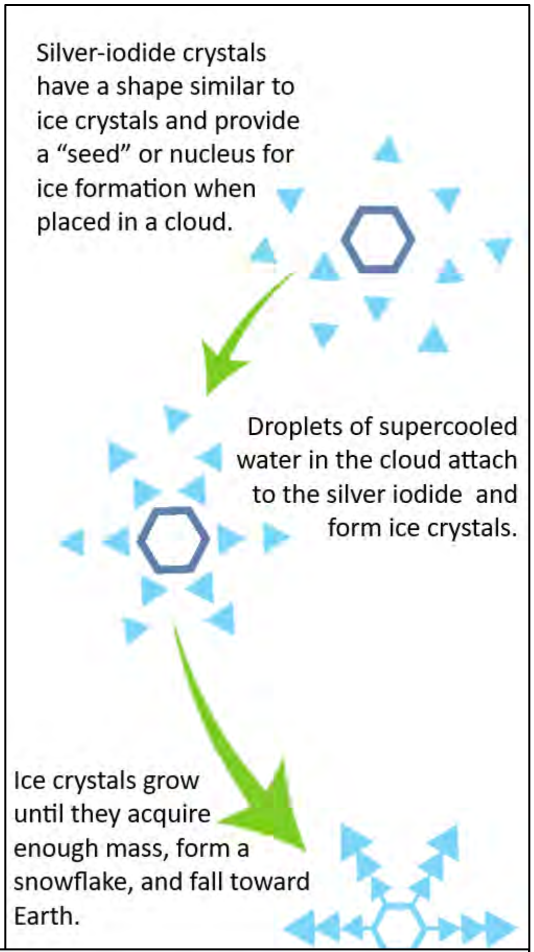
Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.

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

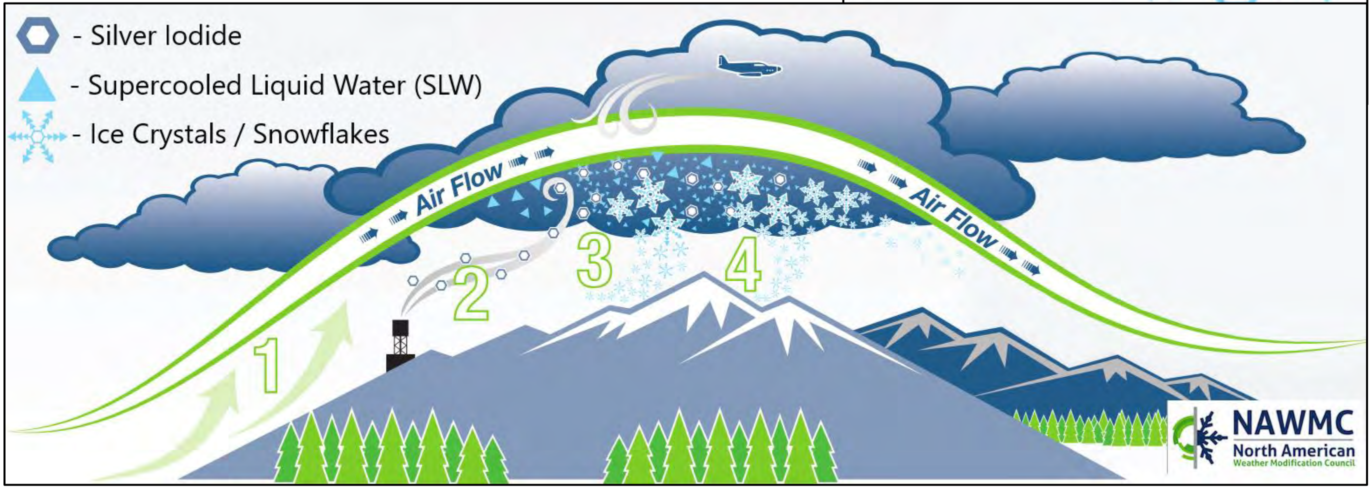
Numerous studies performed by universities, professional research organizations, private utility companies and weather modification providers have conclusively demonstrated the ability for Silver Iodide to augment precipitation under the proper atmospheric conditions.



Silver-iodide crystals have a shape similar to ice crystals and provide a "seed" or nucleus for ice formation when placed in a cloud.

Droplets of supercooled water in the cloud attach to the silver iodide and form ice crystals.

Ice crystals grow until they acquire enough mass, form a snowflake, and fall toward Earth.



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.

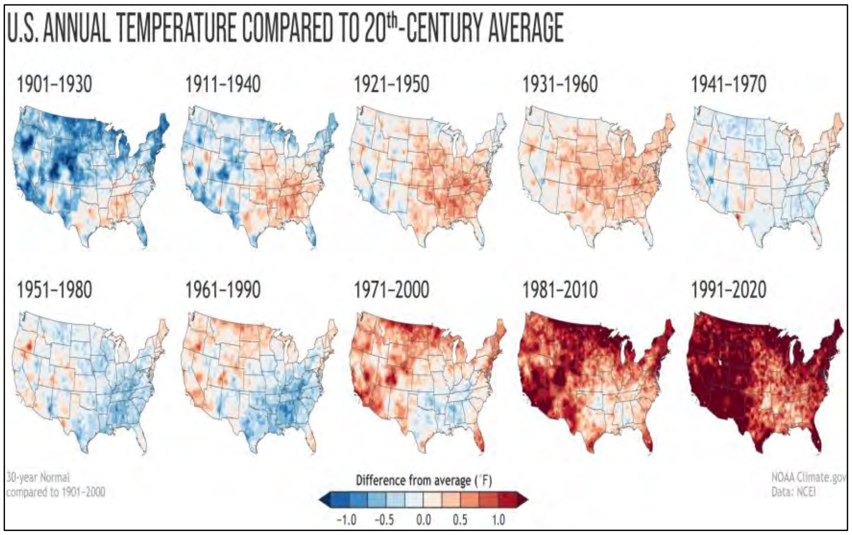


Figure 1 **U.S. Annual Temperature compared to 20th-Century Average**

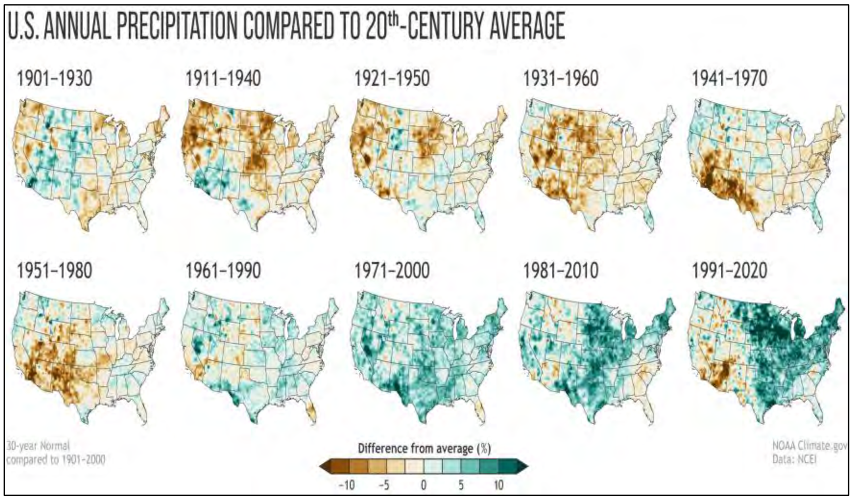


Figure 2 **U.S. annual precipitation compared to 20th-Century average.**

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 well over 40 years. 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 High Uintas Program watersheds.

The Duchesne County Water Conservancy District and the Uintah Water Conservancy District were joined by the Central Utah Water Conservancy District in supporting an operational seeding project beginning in the 2002-2003 winter season. The state of Utah, through the Utah Division of Water Resources and the Lower Colorado River Basin States (LBS) collectively reimburse up to 50% of the cost of this program, and provide funding for an extension period that permits the continuation of the program through the month of April.

The intended target area of this program has been only the south slope of the Uinta Mountains above about 8,000 feet. However, a recent feasibility analysis and discussions with the Division of Water Resources resulted in the addition of the north slope of the Uintas (on the Utah side of the state line) to the program beginning in the 2019-2020 season. For the 2021-2022 water year, the LBS and the UDWR provided funds for the acquisition of a remotely operated ground seeding generator that was placed at Moon Lake. This generator releases higher concentrations of seeding solution than manual generators and permits more regular and consistent operation during the winter months when the road leading up to Moon Lake is frequently closed due to snow pack. This remote generator was once again for the 2022-2023 winter season in conjunction with the manual sites.

The High Uintas Program is tributary to the Colorado River via the Green River, and LBS funds have been used to augment the program beginning in the 2010 water year. The extension period funded by Lower Basin States has been at the beginning of the core project season for the High Uintas, during the month of November each season. The extension provides additional benefit to the primary project sponsors at no additional cost to them. As additional LBS funding benefits, additional ground-based silver iodide generators have previously been added to the program, as well as strategically-located mountain ridge ice detector systems designed to help identify storm periods producing supercooled liquid water which is the target of the cloud seeding efforts.

This report provides information about operational cloud seeding conducted over the target watersheds in the 2022-2023 winter season, including the extension period. Section 2.0 describes the seeding project design and provides maps of the seeded target areas, as well as the locations of the ground-based seeding units (generators) with which the seeding was conducted. Section 3.0 describes the meteorological and computer forecast model data used in the conduct of operations, with some examples presented. Section 4.0 summarizes the seeding operations and documents the seeding generator usage by site and storm event. Section 5.0 provides an overview of statistical evaluations of the effects of the cloud seeding program.

2. PROJECT DESIGN

2.1 Background

The general project design utilized for the High Uintas cloud seeding project is essentially the same as that which has been shown to be effective for over four decades of wintertime cloud seeding in other mountainous regions of Utah. Estimations of seeding effectiveness for long-standing operational seeding projects in Utah have consistently indicated increases in winter season precipitation and snow water content during the periods in which cloud seeding was conducted. The increases for most ground-based programs have averaged approximately 5-10% more than what would have been expected in the absence of seeding, as predicted by historical target/control linear regression analyses.

The target area for the High Uintas project is adjacent to the target area for the Upper Weber Basin (Western Uintas) Project as seen in (Figure 2.1), which has also been conducted for a number of recent winter seasons. As discussed earlier the program was previously expanded for the 2020-2021 water year to incorporate the Northern Slope of the Uinta Mountain Range.

The target area was designed to include elevations of 8000 feet MSL or greater on the south slope of the Uinta Mountains containing river drainages that provide water to either of the sponsoring counties, plus areas providing runoff into Strawberry and Currant Creek Reservoirs. To overcome the impacts of the thermal inversions that is common in the valley south of the Uinta Mountain Range during the winter, NAWC recommends placing ground generators at or above about 7,000 feet in elevation. Due to the prevalence of national forests and Native American Reservations at upper elevations the placement of ground generators above the inversion is no simple task. This was the primary motivation for the LBS to sponsor the deployment of a remotely operated generator near Moon Lake on the southern side of the Uinta Range.

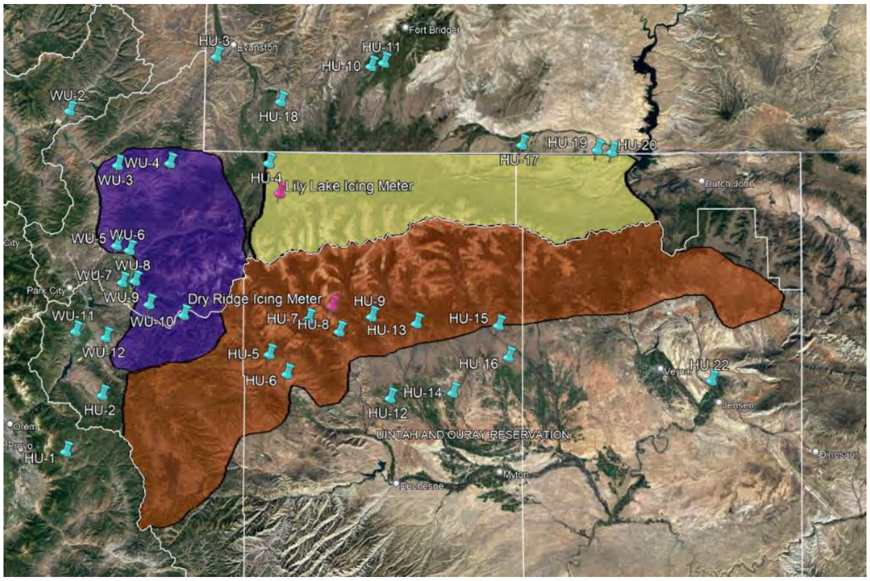


Figure 2.1 Western Uinta Program (purple), High Uinta Program (orange), Northern Slope Extension (yellow)

Regarding the second factor, project duration, Table 2-1 shows average monthly precipitation amounts at three high elevation NRCS SNOTEL sites located within the target area. The month of April is obviously a very productive period based on climatology. Such information was used in specifying the cloud seeding project core operational period.

Table 2-1
Average Monthly Precipitation in the Target Area (inches)

Site	Elev.	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Chepeta	10,300	2.6	2.2	2.2	2.3	2.2	2.6	3.6	2.9
Five Pts.	11,000	2.9	2.3	2.8	2.5	2.2	2.8	2.7	2.9
Trout Cr.	9,400	1.7	1.8	1.7	1.8	2.0	2.5	2.6	2.3

Consideration of the third issue (wind direction) dictates that a significant number of generators should be placed at south flank locations, since a number of the more productive storms have steering level winds from the southeast through west-southwest directions. Another maximum in potentially seedable storms occurs during westerly to west-northwesterly winds, which supports frequent usage of sites on the western side of the Uinta Range. Some seedable situations involve winds with a more significant northerly component (i.e. from northwesterly to northeasterly), and this supports the location of seeding sites on the northern side of the Uinta Range. Operational experience with this program has shown that storms with northerly-component winds may be good seeding candidates, with the enhanced snowfall on the northern slope of the Uintas that frequently carries over to the upper portion of the southern slope (within the target area) as well.

2.2 Seedability Criteria

NAWC has historically followed a selective seeding approach. This has proven to be the most efficient and cost-effective method, and provides the most beneficial results. Selective seeding, or seeding only storms or storm periods 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 the structure of the airmass (temperature, thermodynamic stability, wind flow and moisture content), both in and below the precipitating clouds. The following list provides a summary of the generalized criteria that NAWC uses in the conduct of its wintertime projects in the intermountain west. These criteria are based upon the results obtained in a number of relevant research-oriented weather modification programs.

NAWC Winter Cloud Seeding Criteria

- Cloud bases are near to (ideally) 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 Setup

During the off-season, the ground-based generators are routinely removed from the field for maintenance and testing. NAWC began re-installing the generators in October 2022. The generators were placed at the locations shown in Figure 2.1.

The cloud seeding equipment at each manually operated site consists of a cloud nuclei generator (CNG) unit and a propane gas supply. The seeding solution contains two percent (by weight) silver iodide (AgI), the active seeding agent, complexed with very small portions of sodium iodide and para-dichlorobenzene in solution with acetone. A paper published by Dr. William Finnegan, a well-respected cloud seeding formulation expert of the Desert Research Institute (Finnegan, 1999), indicates that this formulation is superior to others that produce pure silver iodide particles. The modified particles produced by combustion of the revised formulation act as ice nuclei much more quickly, and there are somewhat larger numbers of effective nuclei at warmer temperatures (i.e., about -5°C to -10°C). Figure 2.2 is a photograph of a manually operated, ground-based cloud nuclei generator such as those used for the High Uintas Program. Trained local operators are available to activate each seeding site upon request from a NAWC meteorologist. A cloud nuclei generator is activated by igniting a propane flame in the burn chamber, and then 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 burn chamber at a regulated rate, where microscopic-sized silver iodide (AgI) crystals are formed. The crystals, which closely resemble natural ice crystals in structure, are released at a rate of 8 grams per hour when the 2% (AgI by weight) solution is used. These crystals become active as artificial ice forming nuclei at in-cloud temperatures between -5°C and -10°C (23°F to 14°F).

It is necessary that the AgI crystals become active in supercooled clouds at relatively low altitudes upwind of (or over) the mountain crest. This allows the available supercooled liquid water to be effectively converted to ice crystals which can grow to snowflake size and precipitate onto the mountain barrier. If the AgI crystals take too long to become active, or if the temperature upwind of the crest is too warm, the plume will pass from the generator through the precipitation formation zone and over the mountain crest without producing any additional snowfall in the intended target area.

Figure 2.2 **NAWC manually operated cloud nuclei generator (CNG)**

Manually operated CNGs are maintained at 21 locations specific to the High Uintas program, with in addition to the remotely operated seeding equipment at Moon Lake on the southern flank of the target area. There are now eight sites on the northern side of the target area. Two other sites are used primarily to target the Strawberry Divide area (sites HU1 and HU2), with many of the nearby Western Uintas sites utilized to target this area as well. The network of sites is designed to be effective in generating plumes of seeding material which will pass over the target area in a variety of wind flow situations. A good number of sites primarily designated for use in the Western Uintas Program (WU prefix in Figure 2-1) are also utilized for seeding the High Uintas target area when conditions are favorable for this. Pertinent site information is listed in Table 2-2, corresponding to the site numbers shown in Figure 2.1.

Table 2-2
Cloud Seeding Generator Sites

Site ID	Site Name	Elevation (Feet)	Latitude (N)	Longitude (W)
HU1	Hobble Creek	5870	40°12.22'	111°30.14'
HU2	Wallsburg	6175	40°20.95'	111°23.00'
HU3	Evanston	7000	41°12.70’	111°01.13’
HU4	Bear River East	8223	40°56.54'	110°50.17'
HU5	Hanna Pump House	7019	40°27.60'	110°49.56'
HU6	Hanna	6781	40°24.64'	110°46.03'
HU7	Rock Creek Ranch	7988	40°33.02'	110°41.78'
HU8	Robbins Ranch	7404	40°31.18'	110°35.64'
HU9	Moon Lake (remote)	8100	40°33.25’	110°29.20’
HU10	Black’s Fork	7509	41°11.39'	110°29.87'
HU11	Robertson	7322	41°11.97'	110°27.31'
HU12	Talmage	6945	40°21.53’	110°27.28’
HU13	Yellowstone Canyon	7660	40°32.50’	110°20.30’
HU14	Bluebell	5840	40°26.85'	110°03.72'
HU15	Uinta Power Plant	6932	40°32.27'	110°03.98'
HU16	Neola	6330	40°27.48'	110°02.93'
HU17	Birch Creek	7634	40°58.64'	109°59.48'
HU18	Gilmore Ranch	7550	41°05.91’	110°47.96’
HU19	Manila	6500	40°58.91'	109°44.36'
HU20	Manila East	6230	40°58.57’	109°41.38’
HU22	Jensen	4896	40°23.92'	109°21.49'
W4	Pineview	6407	40°56.39'	111°10.18'
W6	Oakley	6472	40°43.07’	111°18.00’
W7	Kamas	6489	40°38.43'	111°16.77'
W8	Kamas West	6472	40°38.16'	111°19.33'
W9	Woodland	6706	40°34.89'	111°13.81'
W10	Woodland East	7305	40°33.35'	111°06.80'
W11	Midway	5570	40°30.59'	111°28.64'
W12	Heber City	5810	40°29.73'	111°22.52'

2.4 Project Instrumentation

Some specialized instrumentation has been added over the past number of years to enhance cloud seeding guidance during operations within the High Uinta Program area. This includes icing rate meters and, during one previous (2021-2022) season, a radiometer was located on the northern side of the Uinta Range. Both instrument systems were supported by funding from the Lower Basin States. Because SLW is the target of cloud seeding, such a sensor is of benefit both in terms of real-time operational decisions and for later analysis of the frequency of SLW occurrence in relation to winter storm periods. This sensor is similar to sensors which have been installed in other seeding target areas in Utah. Analysis reports on the Utah ice detector data are available on the NAWC website at http://www.nawcinc.com/publications.html. Analyses of the data from these sites have provided valuable insight into the occurrence of SLW during winter storms. Figures 2.3 and 2.4 provide photographs of the installation. The funding for the equipment, installation and maintenance of this site was provided by three Lower Colorado River Basin States and administered by the Utah Department of Water Resources Division.

Figure 2.3 Icing Rate Meter Installation at the Dry Ridge Site

Figure 2.4 **Dry Ridge Sensor Suite**

2.5 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. There were no suspensions of seeding operations during the 2022-23 season.

3. WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

NAWC maintains a fully equipped project operations center at its Sandy, Utah headquarters. Meteorological information is acquired online from a wide variety of 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 provides predictions of ground-based seeding plume dispersion for a discrete storm period in the High Uintas 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 in real-time, based on wind fields contained in the weather forecast models.

Global and regional forecast models are a cornerstone of modern weather forecasting, and an important tool for operational meteorologists. These models forecast a variety of parameters at different levels of the atmosphere, including winds, temperatures, moisture, and surface parameters such as accumulated precipitation. An example of a display from the Global Forecast Systems (GFS) model is shown in Figures 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 a 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 on 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.

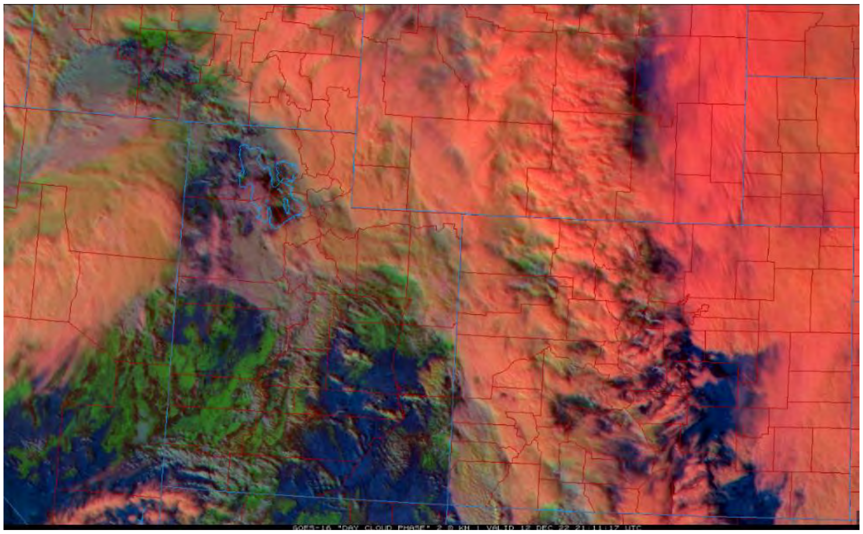


Figure 3.1 Day Cloud Phase satellite image of Utah during the afternoon of December 12, 2022 during a seeded event.

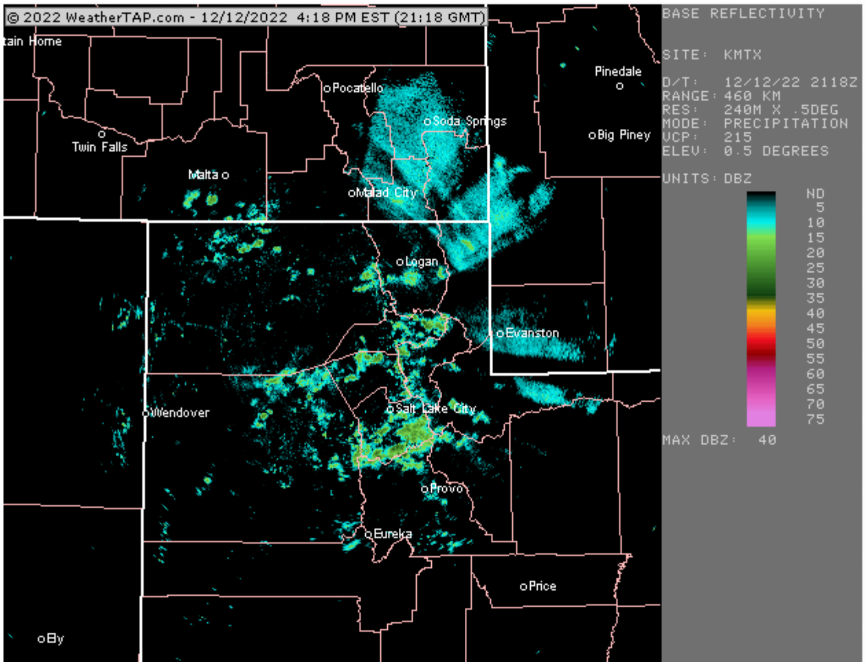


Figure 3.2 Weather radar image over northern Utah during the afternoon of December 12, 2022. Image courtesy of weatherTAP.com.

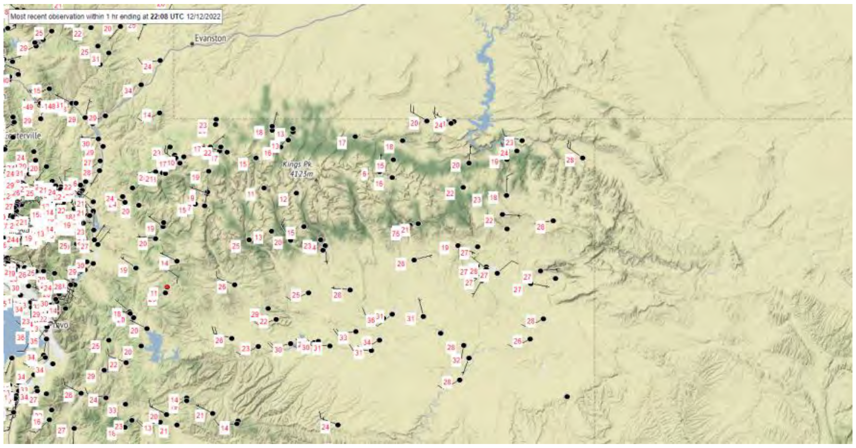


Figure 3.3 Surface map during the December 12 storm event, showing winds and temperatures at a variety of automated sites in an around the Uinta Range.

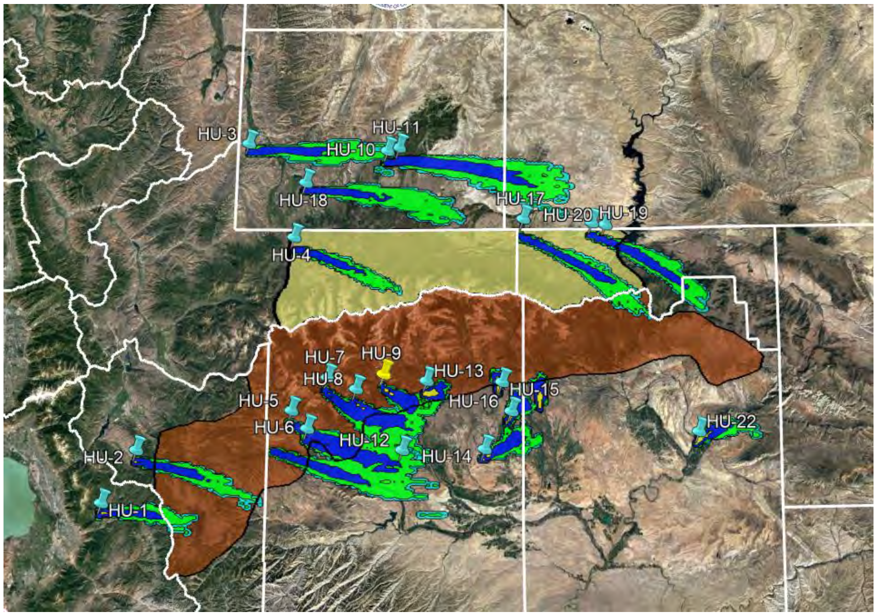
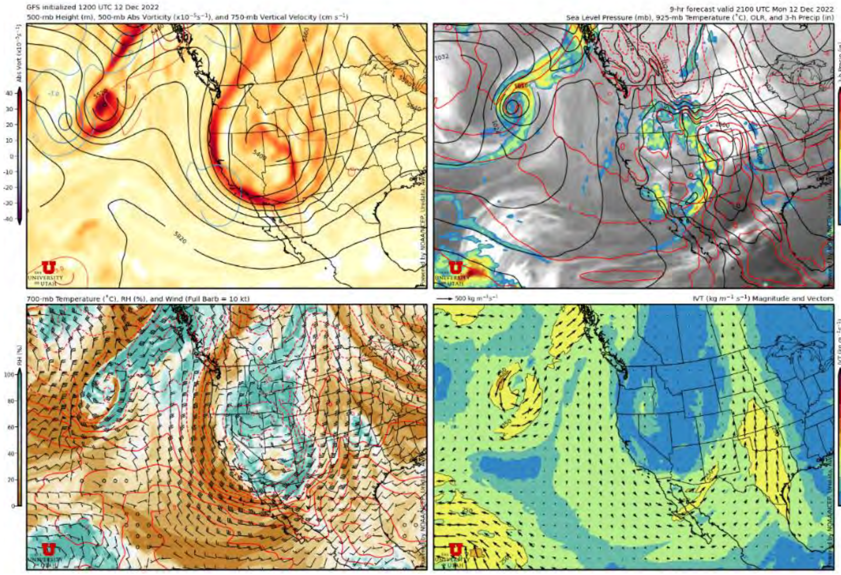


Figure 3.4 HYSPLIT plume dispersion forecast for potential seeding locations during a storm on the evening of December 12, 2023. This is a tool that can be used to help select appropriate sites for a given situation.



Figures 3.5 **GFS model 4-panel data display during a storm event on December 12, 2022. The lower left panel shows winds, moisture, and temperature at the 700-mb level which are especially useful for seeding operations.**

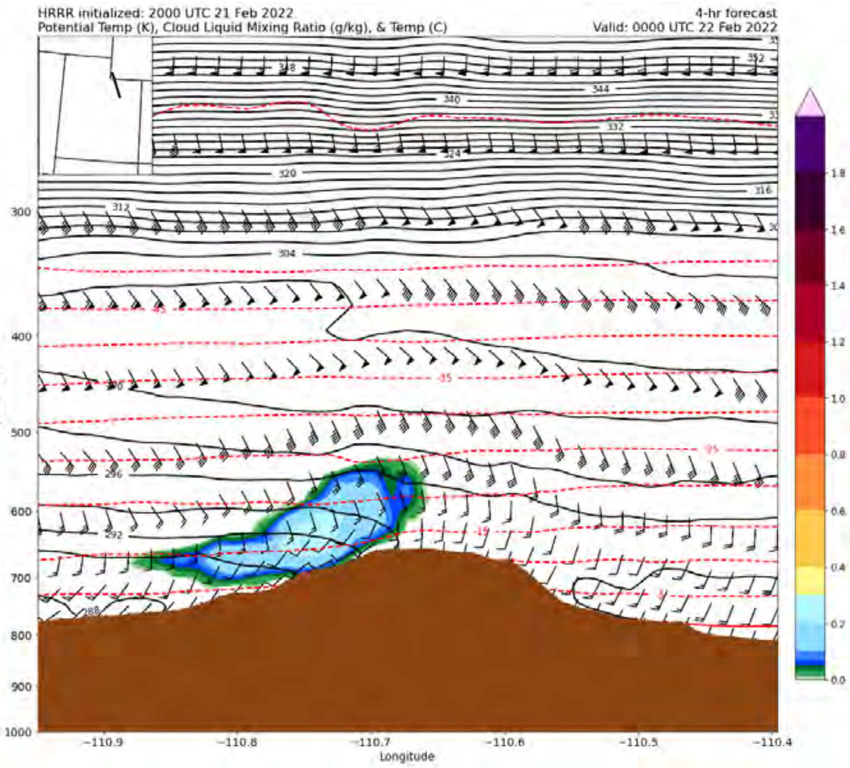


Figure 3.6 **HRRR modeled Cross Section of Liquid Water on February 21, 2023 – Valid at 1700 MST**

4. OPERATIONS

The core 2022-2023 cloud seeding program for the High Uintas contractually extended from December 1, 2022 through April 30, 2023, with an extension period from November 1-30, 2022 funded by the Lower Basin States. During the entire operational season of November 1 – April 30, seeding operations took place over 31 storm periods, with three of these occurring during the extension period in November. Altogether, there were three seeded storms in November, five in December, six in January, five in February, nine in March, and three in April. A cumulative 1,654.75 hours of ground seeding generator operations were conducted during the regular season, and an additional 258.5 hours during the extension period, for a total of 1913.25 hours. Figure 4.1 is a graph of operations this season for the core High Uintas program, compared to a linear usage of the total budgeted hours. Table 4-1 shows the seeding dates and ground generator usage for the storm events, and Appendix B shows detailed site usage data.

Precipitation/snowfall was generally near to below average this season. As of April 1, 2023, SNOTEL observations for the Natural Resource Conservation Service showed snow water content averaging about 187% of normal (median) for the Duchesne Basin and about 163% of normal for sites in the portions of the Uinta Range that compose the Green River Basin. Water year precipitation percentages were 159% of the median for the Duchesne Basin and around 133% of normal for sites in the Green River Basin. By the end of the project (May 1), median snowpack percentages had increased to 222% for the Duchesne Basin and 201% for the Green River Basin. Water year to date percentages (of the mean) on May 1 were 145% for the Duchesne Basin and 128% for the Green River Basin. Figures 4.2 to 4.4 show snow water content and water year precipitation accumulations, and normal, for October 1 through May 1 for target area SNOTEL sites.

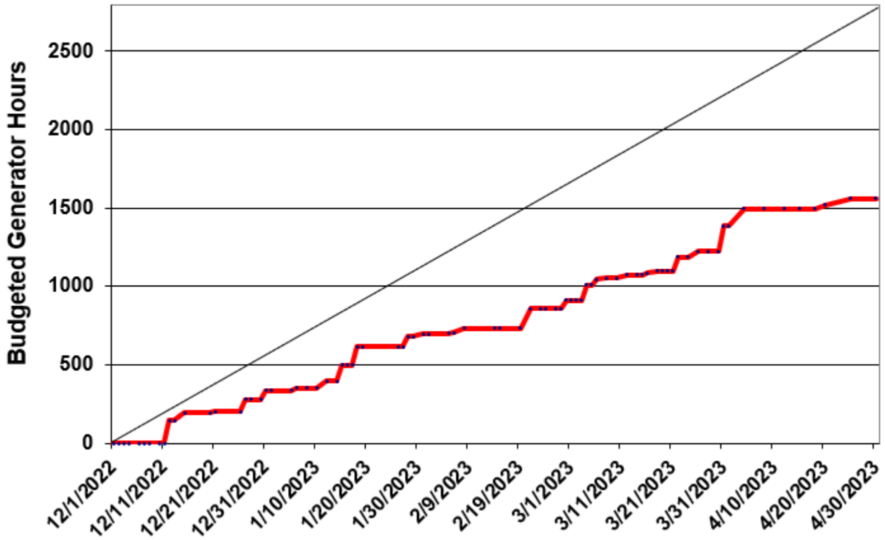


Figure 4.1 **Seeding operations during the 2022-2023 season for the core program (red). Diagonal black line shows a linear usage of total budgeted hours, as a reference.**

Table 4-1
Storm Dates and Number of Generators used in the High Uintas Program

Storm Number	Date	Number of Generators	Operational Hours
1*	November 3	6	41.5
2*	November 9-10	8	98.75
3*	November 28-29	6	118.25
4	December 12-13	8 + 1 remote	145 + 18 remote
5	December 15	6	46.75
6	December 21	1	8.25
7	December 27-28	6	79 + 16.5 remote
8	Dec 31 – Jan 2	6	54.5 + 20 remote
9	January 6	2	18
10	January 10-11	4	44
11	January 14-15	6	100.75
12	January 16-18	8	120
13	January 27-28	3	62.5
14	January 29	2	18.25
15	February 5	1	5.75
16	February 6	1	3.25
17	February 8	5	25.75
18	February 21-22	9	127.75
19	February 27-28	4	52
20	March 4-5	6	97
21	March 5-6	3	38
22	March 8	3	8
23	March 12	4	17.5
24	March 15	2	12
25	March 20	2	13
26	March 22	10	94.5
27	March 24	4	38.5
28	March 29-31	9	162
29	April 3-4	4	109.75
30	April 20	2	15
31	April 24-25	2	45.75
		Core Program Total	**1562.5 + 92.25 remote**
		Extension Total	**258.5**

* Seeding during Lower Basin extension period

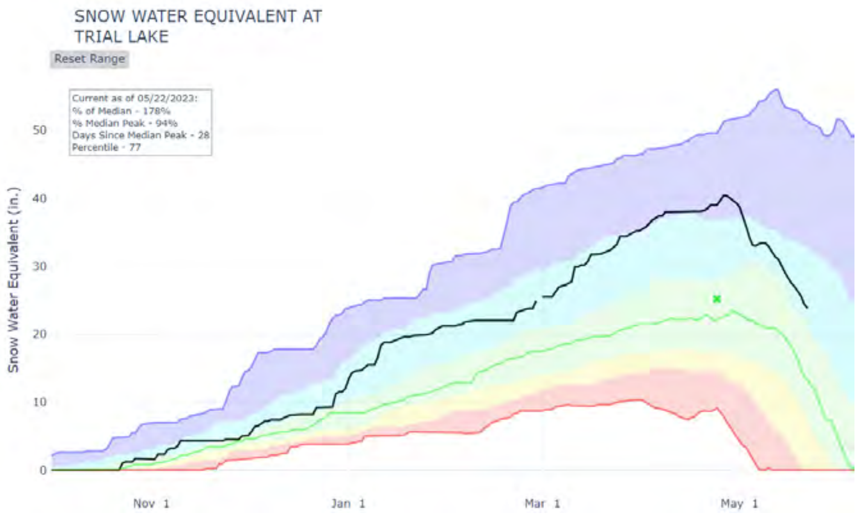


Figure 4.2 NRCS SNOTEL snow water content plot for October 1 2022 through May 22 2023 for the Trial Lake SNOTEL, UT in the western Uintas. Black line is the 2022-23 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.

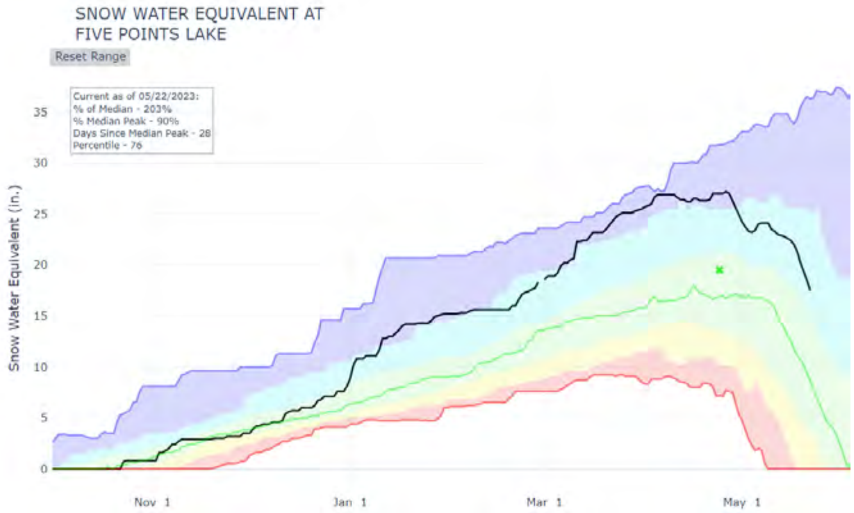


Figure 4.3 NRCS SNOTEL snow water content plot for October 1 2022 through May 22 2023 for the Five Points Lake SNOTEL, UT in the central portion of the Uintas. Black line is the 2022-23 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.

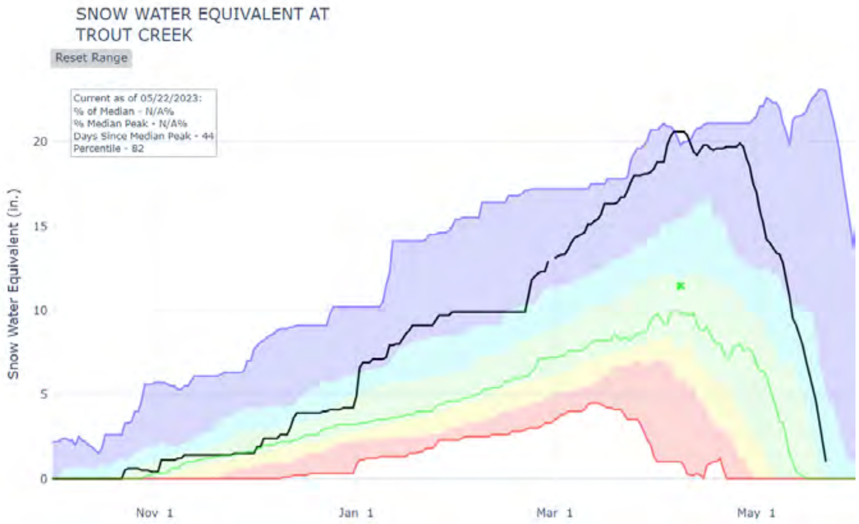


Figure 4.4 **NRCS SNOTEL snow water content plot for October 1 2022 through May 22 2023 for the Trout Creek SNOTEL, UT on the eastern side of the Uintas. Black line is the 2022-23 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.**

4.1 Operational Procedures

In operational practice, 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.

4.2 Operational Summary

A brief synopsis of the weather during the operational seeding period is provided below. All times reported are local, either in MST or MDT. When wind direction information is given, it is the direction from which the wind is blowing. For example, a northwest wind is blowing from the northwest towards the southeast. The temperature at the 700 mb level (~9,500 feet above sea level during the winter) is commonly referenced, since temperature is an important factor when determining the seeding potential of an event. Data from the ice detector site at Dry Ridge (elevation 11,540 feet) can also be an important indicator of the presence of supercooled water in the target area, and thus seeding potential.

November 2022

The weather pattern was quite active and wet through the first half of November and brought two seeded storm periods, one on November 3rd and another November 9th-10th. A cool and mostly dry northerly flow pattern briefly settled in around mid-month before another active weather pattern redeveloped late in the month and brought an additional seeded storm period November 28th-29th.

The first seeded event of the season occurred on November 3rd as a longwave trough over the Desert Southwest pushed eastward through southern California/Nevada during the morning hours and evolved into a closed low over Arizona during the afternoon. The track and position of the low forced the winds over northern Utah to become northerly in direction and caused moisture embedded within the flow to bank into the northern slopes of the Uintas. Beginning around 0900 MDT, radar returns and satellite imagery suggested that orographic (terrain induced) precipitation was occurring on the northern side with this type of precipitation continuing through the afternoon. Dry Ridge recorded several icing cycles through the morning and afternoon hours, indicating there was at least patchy areas of liquid water development, necessary for effective seeding. As such, seeding operations were initiated around 0900 MDT and continued until early evening on the 3rd when conditions dried out and skies cleared. Seeding operations utilized mostly sites on the northern side and near the northern target area. Precipitation totals were generally in the 0.1-0.3" range (water content.

A strong cold front pushed eastward and through the area on the morning of November 9th. Seeding began around 0600 MST on the 9th as the frontal band moved through and brought a period of moderate to briefly heavy snowfall. A good amount of icing was observed at Dry Ridge during the frontal passage, with a total of 6 icing cycles there through the morning hours. Southwesterly winds ahead of the front quickly shifted northwesterly behind its passage with heavy snowfall transitioning to a more orographic (terrain induced) showery mode that persisted overnight into the early morning hours of the 10th. 700mb temperatures fell from near -2°C ahead of the front to near -14°C in the early morning hours of the 10th. Seeding ended around 0800 MST on the 10th with drying conditions.

A fast-moving cold front affected the area during the afternoon of November 28, which was followed by a cold and moist northwesterly flow pattern that kept snow showers lingering over the northwestern Uintas until mid-day on the 29th. Temperatures were much colder behind the front, falling from about -5°C ahead of the front on the morning of the 28th to near -15°C in the overnight hours into the morning of the 29th. Seeding was conducted from one site on the southern side and from several sites in the western Uintas program. No icing cycles were observed at Dry Ridge throughout the event but HRRR cross sectional modeled data suggest that super cooled liquid water values throughout the event range between 0.2-0.3 g/kg. Precipitation totals for this storm event range from about 0.2-0.6".

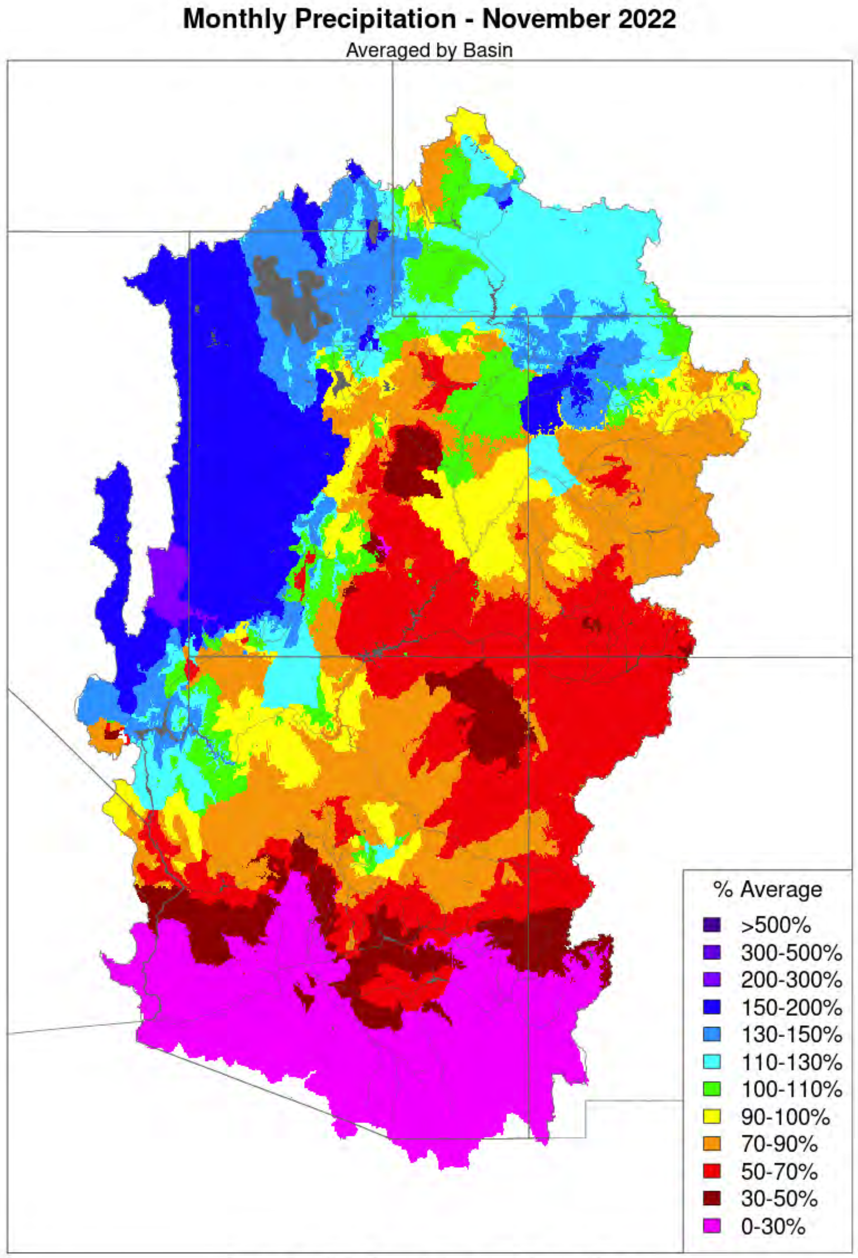


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Figure 4.5 November 2022 precipitation, percent of normal

December 2022

December was the first month of operations for the core program for the High Uintas cloud seeding program. The month of December was quite wet and stormy with the Uinta Range receiving nearly twice the normal monthly precipitation and snowfall. Activity was evenly spread throughout the second half of the month with a storm system impacting the region every several days. In total, there were five seeding storm periods in December.

A longwave trough entrenched across the western U.S. brought an extended period of snowfall which began during the evening hours of December 11th as a cold front tracked northwest to southeast across Utah. A significant amount of icing was recorded at Dry Ridge along and behind the frontal passage with a total of 12 icing cycles being reported there from approximately 1700 MST on the 11th to 0100 MST on the 12th. By the morning of the 12th, the cold front had pushed off to the southeast, but a cold northwesterly flow pattern remained in its wake which allowed snow showers to persist across the northern slopes of the Uintas until the mid-morning hours on the 13th. Dry Ridge did not record any additional icing cycles throughout the 12th or into the morning hours of the 13th. Seeding began from several sites on the southern side after 1800 MST on the 11th and continued overnight into the morning hours of the 12th. Seeding operations then shifted to sites on the northern side on the 12th into eh morning of the 13th as the flow became unfavorable for sites on the south side. This storm event brought about0.4-0.9" of water content to the area.

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 sites located on the northern side from about 0700 MST until snow showers tapered off after 1600 MST. Up to 0.3" of liquid water equivalent were recorded on the northern side of 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. Most of the showers occurring ahead of the cold front were falling from a high cloud deck which is not favorable for seeding. Additionally, Dry Ridge did not record any icing cycles throughout the morning hours on the 21st, so no seeding operations were conducted. The cold front then arrived in northern Utah around 1600 MST and pushed southward across the Uintas between 1700-1900 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. One CNG sites on the southern site was activated to target increasing shower activity along the frontal passage but was later turned off as the cloud deck that snow was falling from exhibited icy characteristics. Between 0.1 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. Dry Ridge recorded two icing cycles during this period. 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 favorable for flow regimes of southwesterly to westerly flow were activated right as the cold front pushed into the target area around 2000 MST on the 27th and ran overnight and through morning hours on the 28th. Most sites were turned off in the morning and early afternoon hours on the 28th but one site remained on until snow showers tapered off after 1800 MST. Dry Ridge recorded five icing cycles from the night of the 27th into the 28th with no additional cycles during the day on the 28th. Up to 1.3” of liquid water equivalent were recorded in the target area during this storm event.

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 southwestern slopes of the Uinta Range. A few CNG sites were activated during the morning and afternoon hours of the 31st as satellite imagery and radar returns revealed that orographic induced precipitation was occurring. Snow showers continued through the night, but seeding operations were concluded in the early evening hours due to the atmospheric temperature profile becoming isothermal (stable). From 0100 to 1900 MST on the 31st, Dry Ridge recorded 10 icing cycles. Moderate to heavy snow persisted across the southern portions of the Uinta Range throughout January 1st, as a steady feed of moisture continued to stream into northern Utah within the southwesterly flow regime. No icing was observed at Dry Ridge on the 1st but seeding operations were reactivated at sites on the southern side in the evening hours as the isothermal layer that developed had eroded due to cooler temperatures at 700mb filtering in. Seeding continued overnight into the morning hours of the before ending between 1000-1200 MST on January 2nd with drying conditions.

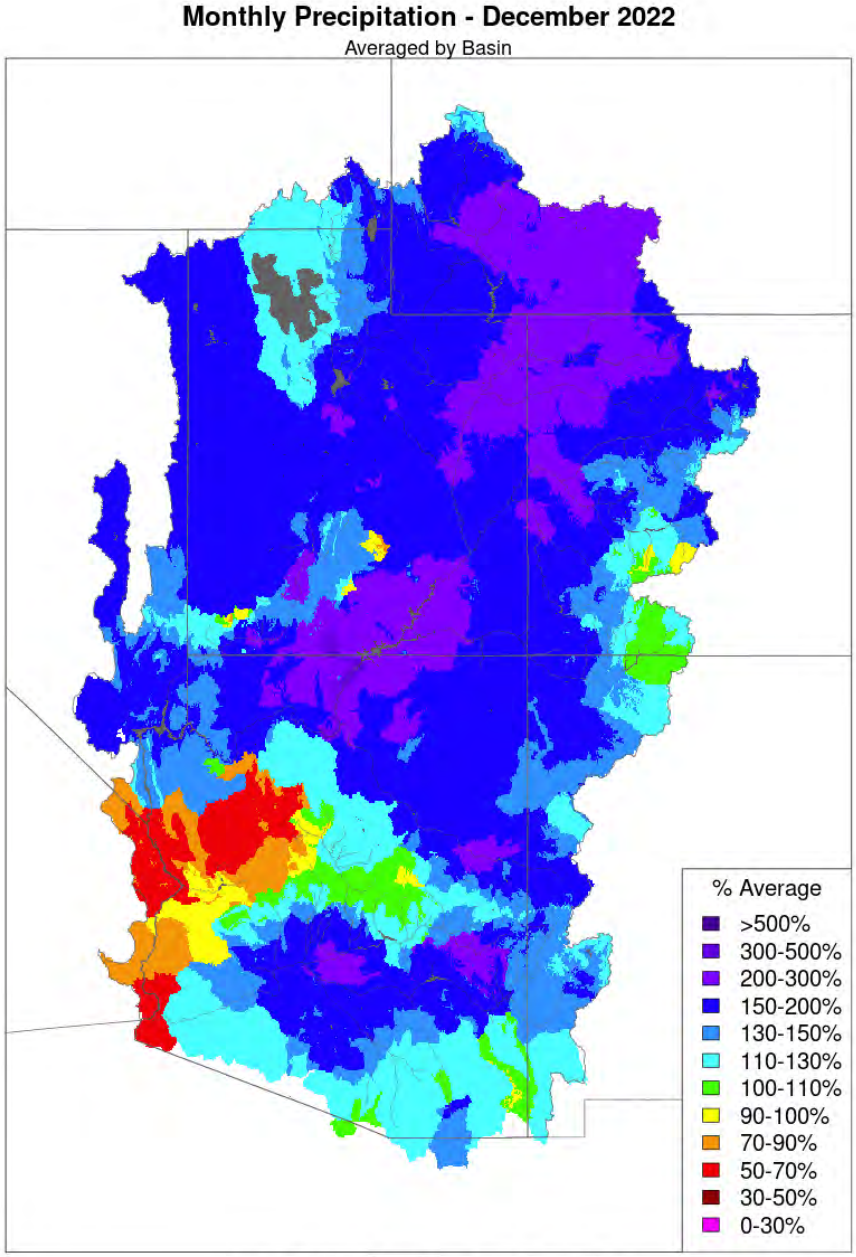

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Figure 4.6 December 2022 precipitation, percent of normal

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 Uinta Range. Seeding was conducted for the High Uintas cloud seeding program during six storm events in January.

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 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. A couple seeding sites on the western side were activated on the morning of the 6th and ran through the afternoon hours. No icing was observed at Dry Ridge. By 1800 MST, 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 0.1-0.3” range (liquid water equivalent).

Utah came under the influence of a rather moist southwesterly flow pattern on the morning of January 10th 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 because of this increase in moisture with snow levels rising to near 6000 feet MSL. 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 north-to-south-oriented 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, dropping from around -3°C to near -10°C. Seeding sites on the western side as well as on the southern side were activated around 1600 MST and remained on overnight into the morning hours of January 11th. Dry Ridge recorded six icing cycles during this time. 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.

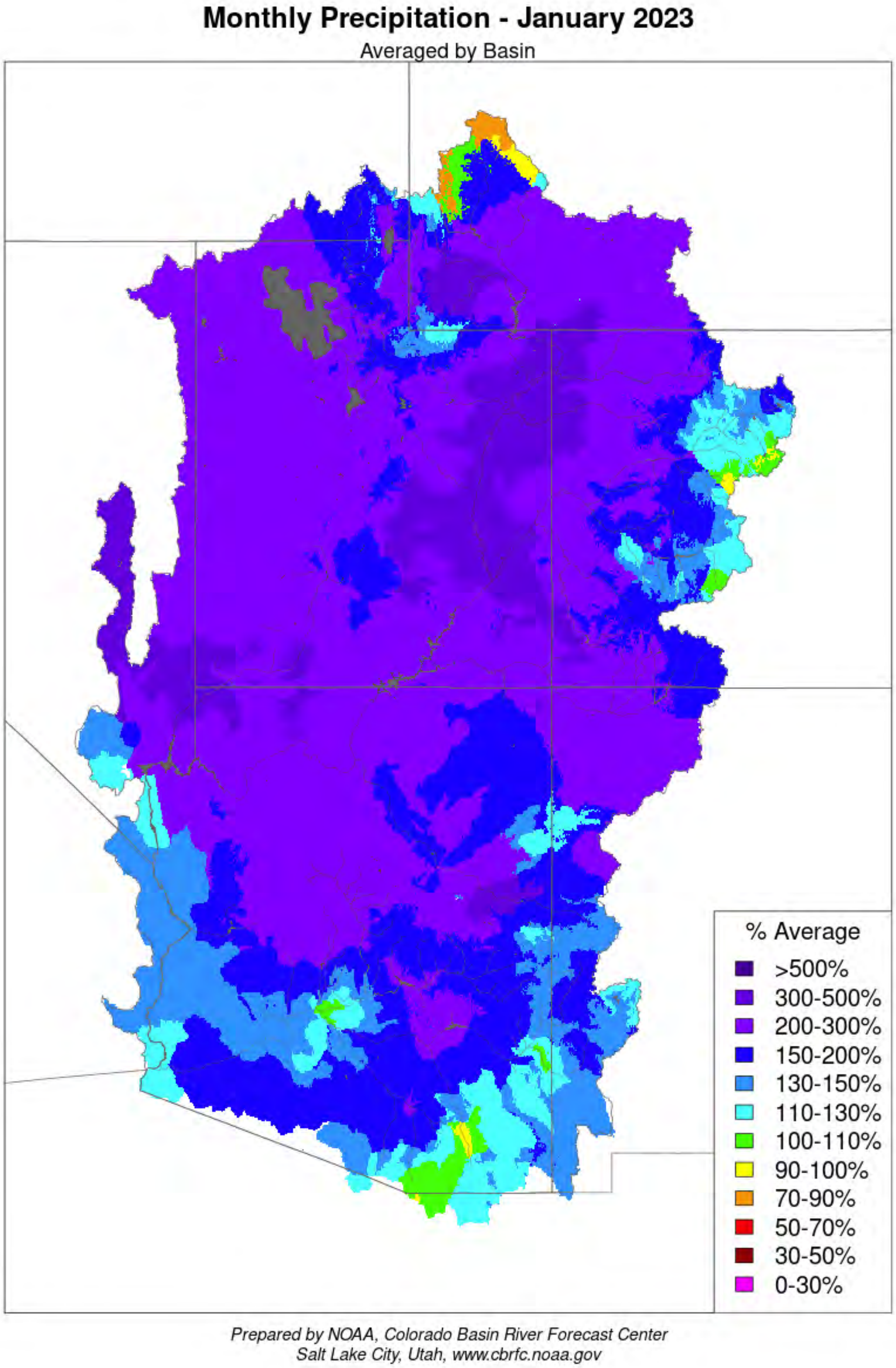
An upper-level trough approaching the Great Basin region on the evening of January 14th impinged a moist southerly flow pattern over northern Utah. As a result, widespread precipitation filled in over the program area and continued overnight into the pre-dawn hours of the 15th. Surface observations revealed that there was a strong stable layer (temperature inversion) in place across the Uinta Basin. As such, seeding was initiated, but only from sites that were located above the stable layer at around 7000 feet in elevation. Snow showers continued throughout the day on the 15th and 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 southerly to west/northwesterly. Seeding was concluded in the morning from sites that are unfavorable in northwesterly flow but continued from southern sites into the early evening hours before conditions dried out after 1600 MST. Dry Ridge recorded several icing cycles in the evening hours of the 14th but did not pick up anything overnight or throughout the day on the 15th. Total snow water equivalent (SWE) for this event ranged from 0.3”-0.7”.

An upper-level trough with a few embedded shortwave features made its way across the Great Basin/Desert Southwest region between January 16-18. The first such featured within a southwesterly flow regime moved across the area on the evening of the 16th into the morning of the 17th. Due to a stable layer (inversion) being present in the Uinta Basin, seeding was only conducted from CNG sites on the southern side located about 7000 feet in elevation after about 1700 MST on the 16th. Seeding continued overnight until about 0800 MST on the 17th after which precipitation briefly tapered off. A secondary feature moving through Arizona during the afternoon hours, reintroduced moisture to the area and caused the flow aloft to shift from southwesterly to northerly. As such, seeding was reinitiated but now focused on the northern side of the target area. Seeding continued until showers dried out around 0800 MST on the 18th. All in all, Dry Ridge only recorded two icing cycles throughout the entire 2-day period, once around 1200 MST on the 16th and again around 1100 MST on the 17th. Precipitation totals were generally in the 0.2-1.0” range throughout the target area, with the highest amounts being observed on the southern slopes.

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 on the western side 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, after which conditions dried out. Dry Ridge only recorded one icing cycle during this period. SWE totals from this event were in the 0.2”-0.6” range.

The last seeding event of January took place on the 29th as the last in a series of shortwave troughs dove southward out of the Pacific Northwest and pushed an Arctic Frontal boundary across Utah during the morning and afternoon hours. The front reached the Uinta Range around 1000 MST and caused southerly winds to shift northerly. Snow showers increased and became heavy along and behind the front passage and 700mb temperatures fell from around -8°C ahead to near -15°C. Moisture was rather limited with this system and no icing cycles were observed at Dry Ridge. As a result, only two CNG sites were activated for the event, beginning around 1000 MST and ending just prior to 2000 MST. Between 0.1 and 0.9 inches of SWE was observed throughout the target area.

Figure 4.7 shows the January precipitation as a percentage of the monthly median, with total generally over 150-200% of the monthly average on the southern side and around 110-130% of the normal amounts on the north side of the Uintas.



Monthly Precipitation - January 2023

Averaged by Basin

Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

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

February 2023

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 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.

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 between the surface and about 720mb. As the atmosphere moistened up through the afternoon hours, snow showers finally started reaching the surface and continued until skies cleared out after 2000 MST. Dry Ridge icing meter did not record any icing cycles during this storm event, due to moisture being somewhat limited. As such, seeding was only conducted from one CNG site from approximately 1400 MST to 2000 MST. Total snow water equivalent (SWE) for this event ranged from 0.1-0.3”.

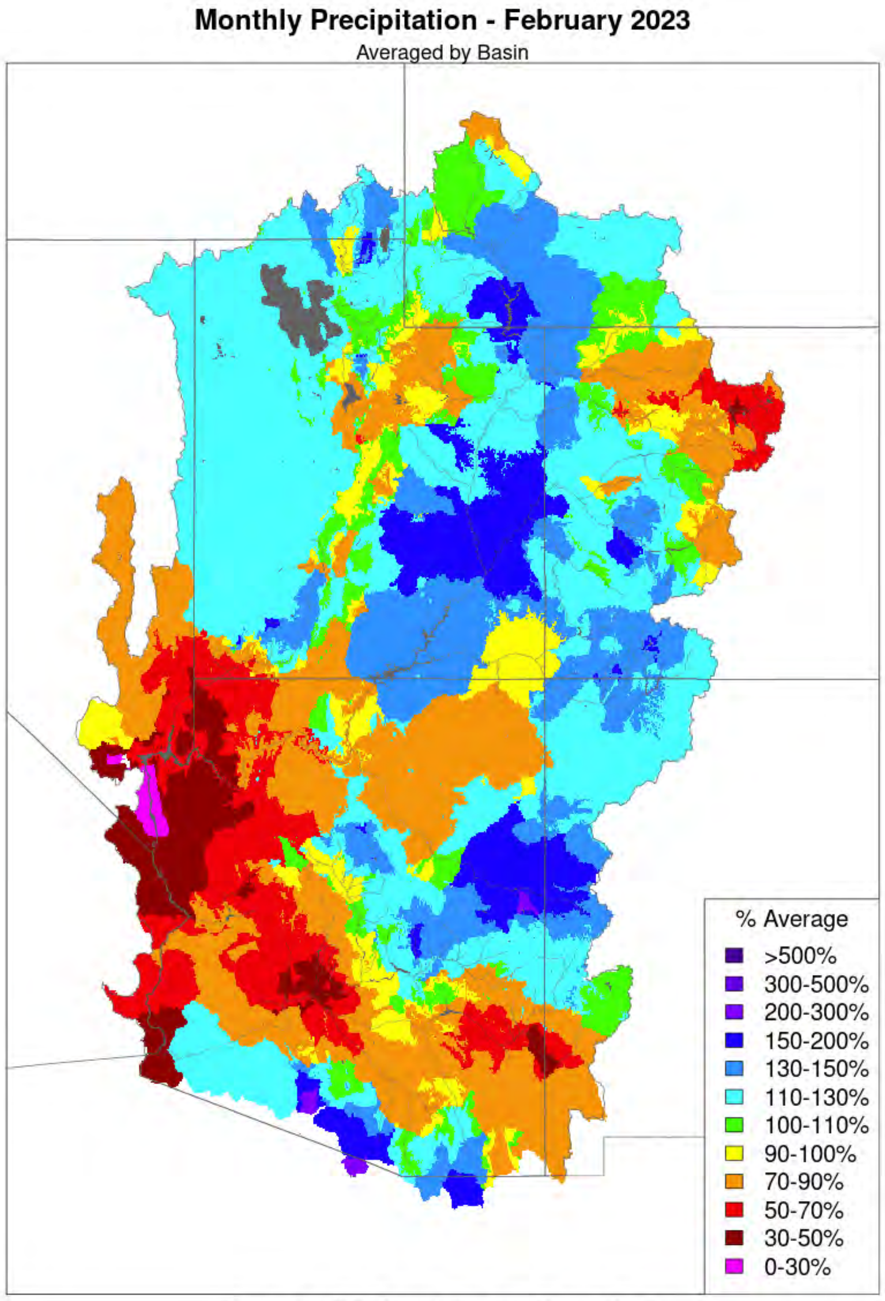
The next in the series of storms began to impact Utah on the morning of February 6th. This next trough dug southward out of Idaho during the early morning hours then pushed off to the south later in the afternoon and evening. As the system dug southward in the early morning hours of the 6th, it brought 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. Again, moisture was very limited with this next system and no icing cycles were recorded at Dry Ridge. Given the lack of moisture, only one seeding site was run throughout the morning and early afternoon hours. Total snow water equivalent (SWE) for this event was around 0.1”.

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 first developed around 1500 MST as the cold front moved in and continued until conditions quickly dried out after 2000 MST. Dry Ridge did not record any icing cycles but seeding operations were conducted from several sites on the northern side as satellite and radar indicated that snow showers had convective characteristics. 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 system brought heavy snowfall to portions of northern Utah as well as 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 stalled over the program area overnight into the morning hours of the 22nd. The 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. Numerous seeding CNG sites were activated on the southern side during the early afternoon and evening hours of the 21st and remained on overnight until conditions dried out during the morning hours of the 22nd. The Dry Ridge icing meter picked up several icing cycles overnight. Total snow water equivalent (SWE) for this event ranged from 0.9-1.9”.

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 on the upper air balloon sounding launched out of Salt Lake City. 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 favorable in southwesterly flow 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 conditions dried out. Total snow water equivalent (SWE) for this event ranged from 0.6-0.8”.

Figure 4.8 shows February precipitation as a percentage of average, with the eastern and northeastern portions of the Uintas receiving up to about 150% of normal.



Monthly Precipitation - February 2023

Averaged by Basin

Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

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

March 2023

The weather pattern through the month of March featured an active subtropical jet stream that brought several significant and moisture rich storm events to the region. The state of Utah, as a whole, saw well above normal precipitation for the month. Due to the fairly regular frequency of storm events in March, there were a total of nine seeded storm periods.

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 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 south 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. Seeding sites on the southern side were initiated beginning around 1600 MST on the 4th and ran up until conditions dried out after 1000 MST on the 5th. No icing cycles were recorded at Dry Ridge, likely due to most of the snowfall originating from a higher cloud deck. Storm total SWE was in the 0.4-0.6” range across the target area.

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 that had 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 became stalled over central Utah on the morning of the 5th conditions further north and over the Uinta Range drying out. The dry break was brief however, 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 located on the southern side of the range were activated on the evening of the 5th and ran overnight into the morning hours of the 6th before ending. Precipitation totals were mostly in the 0.6 – 0.9” range during this event.

A disorganized trough on March 8 resulted in some widespread convective shower activity beginning in southwesterly flow after midday. This activity lasted through the afternoon and had generally ended in the early evening after sunset. 700mb temperatures fell to near -12°C as the core of the trough moved overhead Utah during the afternoon hours which proved favorable for seeding activity. Most areas of the Uintas received a few inches of snowfall with about a quarter to half inch of water content, favoring southern and western portions. There were no icing cycles recorded at Dry Ridge.

Another disorganized trough moved northeastward through Utah on March 12 and brought scattered convective shower activity to the Uinta Range within a southwesterly flow pattern. This activity first developed around midday and had generally ended around 1800 MDT, and although, temperatures were near -4/-5°C it appeared favorable for some seeding from south-side sites. Again, no icing cycles were observed at Dry Ridge. Precipitation totals during this event ranged from about 0.1 – 0.3" at SNOTEL sites in the target area.

A significant Atmospheric River and an associated cold front combined to produced a band of heavy snowfall across northern Utah on the morning of the 15th. This moisture rich front slowly made its way 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 along the frontal band gave way to showery convection which continued across the region until conditions dried out after 1800 MDT. Although the upper-level flow was northwesterly in direction the low-level flow was westerly. As a result, only a few CNG sites on the western sde were initited. Upwards of 0.6-1.2" of SWE was observed across the program area.

A large trough made its way onshore and into California on the evening of the 19th which 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 Uinta Range. Showers and thunderstorms 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 from a few sites on the southwestern side of the program from roughly 1200 MDT through 2000 MDT. All in all, the seeding area picked up around 0.2-0.6" of SWE and Dry Ridge did not record any icing cycles.

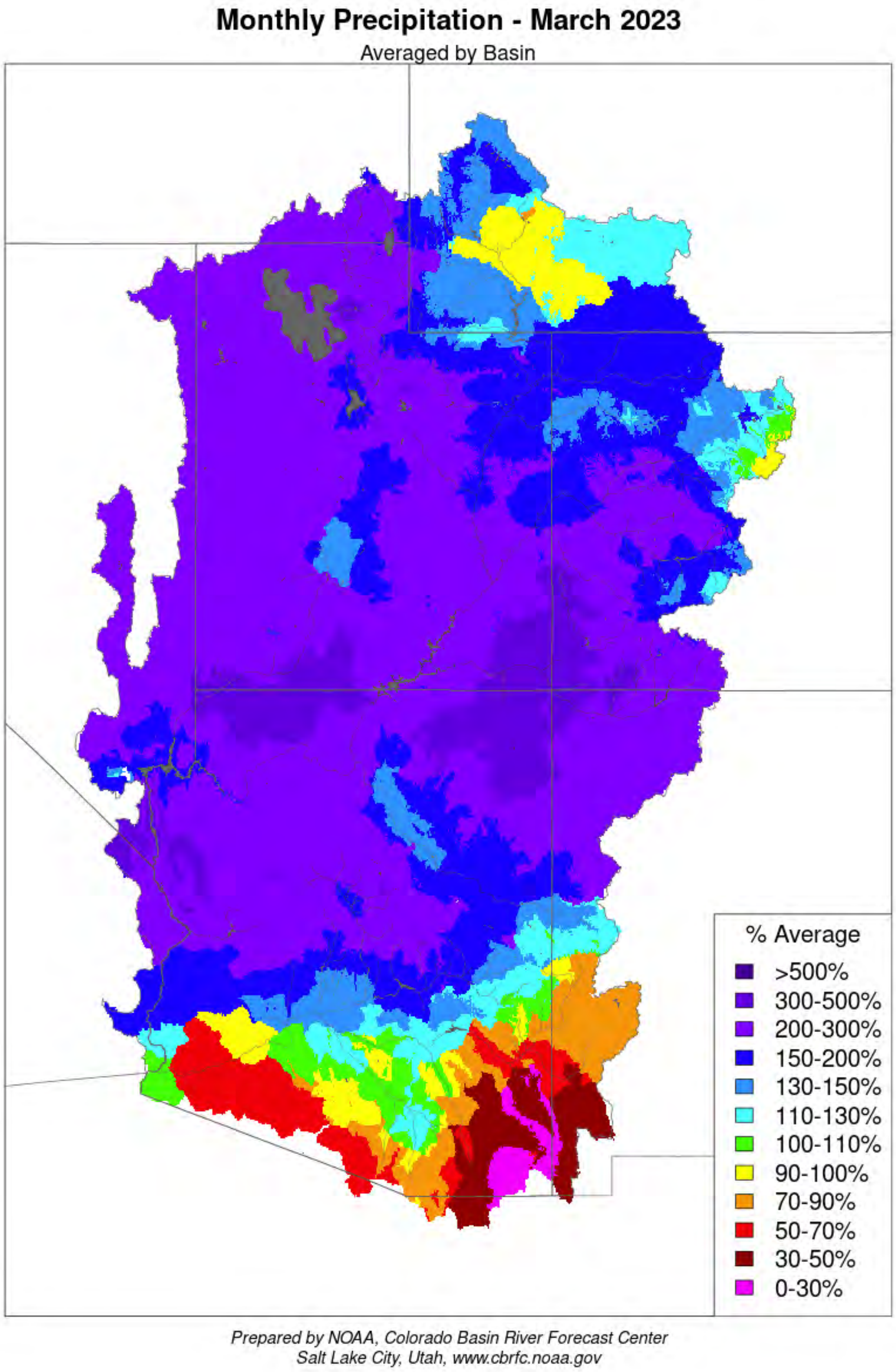
A splitting upper-level trough made its way through Utah during the early morning hours on March 20th. The southern portion of the split system dug too far south to have an appreciable impact on the High Uinta target area. The northern section however, pushed a weakening cold front southeast and across Utah, with it crossing the Uintas between late morning and early afternoon. Strong, dry, and warm southwesterly flow ahead of the cold front quickly turned northwesterly and 700mb temperatures fell from -2°C down to -10°C. Precipitation was largely confined to the frontal band and only lasted for a few hours before conditions dried out early in the evening hours. Seeding was conducted from numerous sites on the southern side, including those located in the Uinta Basin. Around 0.3-0.7" of precipitation was observed at SNOTEL sites around the Uintas and Dry Ridge recorded three icing cycles.

A broad and moist Pacific trough gradually slid eastward across the Great Basin region and forced a cold front into Utah during the afternoon hours on March 22. Deep layer moisture embedded within a southwesterly flow regime ahead of the front caused moderate to heavy precipitation to develop early in the morning hours. As the cold front crossed northern Utah in the afternoon, ongoing precipitation turned showery and the flow aloft shifted from southwesterly to northwesterly. Temperatures at 700mb cooled to near -7°C and several convective showers developed. Seeding was conducted from numerous sites on the southern side beginning in the morning and lasted up until showers ended early in the evening. Total SWE with this system was around 0.3-0.7".

A cold front with mid-winter like temperatures brought a good seeding opportunity on March 24. Some low-level moisture streaming in from the west ahead of the front produced clouds fairly rich in liquid water. Seeding began later in the morning using sites on the western side of the Uinta Range and continued through the afternoon as the frontal band moved through and brought a brief period of heavy snowfall. The 700mb temperature dropped from -9°C ahead of the front to near -17°C behind its passage. Seeding ended later in the evening as it became apparent that conditions were drying out. Dry Ridge only recorded one icing cycle with it occurring around 2000 MDT. Precipitation totals were generally in the 0.3 – 0.5" range (water content).

The last seeding event of March 2023 occurred as a cold front swept across northern Utah on the evening of March 29 into the morning of March 30. The cold front reached the Uinta Range around 2100 MDT on the 29th. 700mb temperatures fell to near -7°C as the front pushed through and the wind shifted from southwesterly to west-northwesterly. Seeding was conducted from sites on the southern side. Seeding continued overnight and through the morning hours of the 30th as low-level moisture continued to stream in from the west and support additional snow shower development. Seeding was concluded from the southern sites during the afternoon hours on the 30th as the flow shifted from westerly to northwesterly and precipitation became focused on the northern slopes of the Uinta Range. From there, seeding continued through the evening and overnight hours before ending around midday on the 31st as conditions dried out. Dry Ridge recorded four icing cycles from the evening of the 30th into the morning of the 31st. Around 0.2-0.6" of precipitation was observed at SNOTEL sites around the Uintas and Dry Ridge recorded three icing cycles.

Figure 4.9 shows the March 2023 precipitation totals as a percent of median with the entire region observing well above normal precipitation for the month.


Monthly Precipitation - March 2023

Averaged by Basin

Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

Figure 4.9 March 2023 precipitation, percent of normal

April 2023

The weather pattern through the month of April was significantly drier when compared to the rest of the 2022-2023 winter season, but still featured near normal precipitation and below normal temperatures for the area. There were three seeded storm events throughout the month.

A large trough on April 3-4 resulted in some snowfall across the Uintas in a northwest to northerly wind pattern. The 700 mb temperature fell from about -7 to -13° C during this time period. Seeding was conducted from several sites on the northern side from the afternoon of the 3rd until late evening on the 4th. Lower-level moisture was somewhat lacking initially with this system but there appeared to be significant seedable cloud development during the seeded portion, with good orographic effects occurring on the northern slopes. The Dry Ridge site recorded two icing cycles during the overnight hours. Precipitation was generally confined to the northern side of the Uintas, ranging between 0.7-1.3" in water content.

A cool and moist northwesterly flow pattern encompassed the western U.S. on April 20th. A subtle shortwave trough digging southward through Utah within this northwesterly flow pattern triggered snow showers development on the northern side of the Uintas during the late morning and afternoon hours. Seeding was conducted at a couple of sites on the northern side to target this activity and was later concluded in the early evening hours as showers dried out. 700mb temperatures averaged around -10°C throughout the event and Dry Ridge recorded one icing cycle in the morning. SNOTEL sites around the target area on the northern side reported between 0.3-1.2" of precipitation accumulation.

A strong cold front pushed through northern Utah during the evening of April 24 into the morning of April 25, with temperatures dropping from near 0°C to around -10°C at 700 mb. Moisture pooled across the northern Utah caused widespread convective showers to develop ahead of the cold front during the afternoon hours of the 24th on the northern side of the Uinta Range. Even though temperatures were marginal (around 0 to -2°C) seeding was initiated from sites on the northern side as these favorable convective showers drifted southward and into the target area. Seeding continued overnight as the front pushed south and also continued throughout the day on the 25th as additional moisture streamed in form the north and snow showers persisted. Dry Ridge recorded one icing cycle during the overnight period and two during the late afternoon hours on the 25th. Precipitation totals during this event ranged from about 0.1 – 0.3" at SNOTEL sites in the target area.

Figure 4.10 shows precipitation as a percentage of the median values for the month of April.

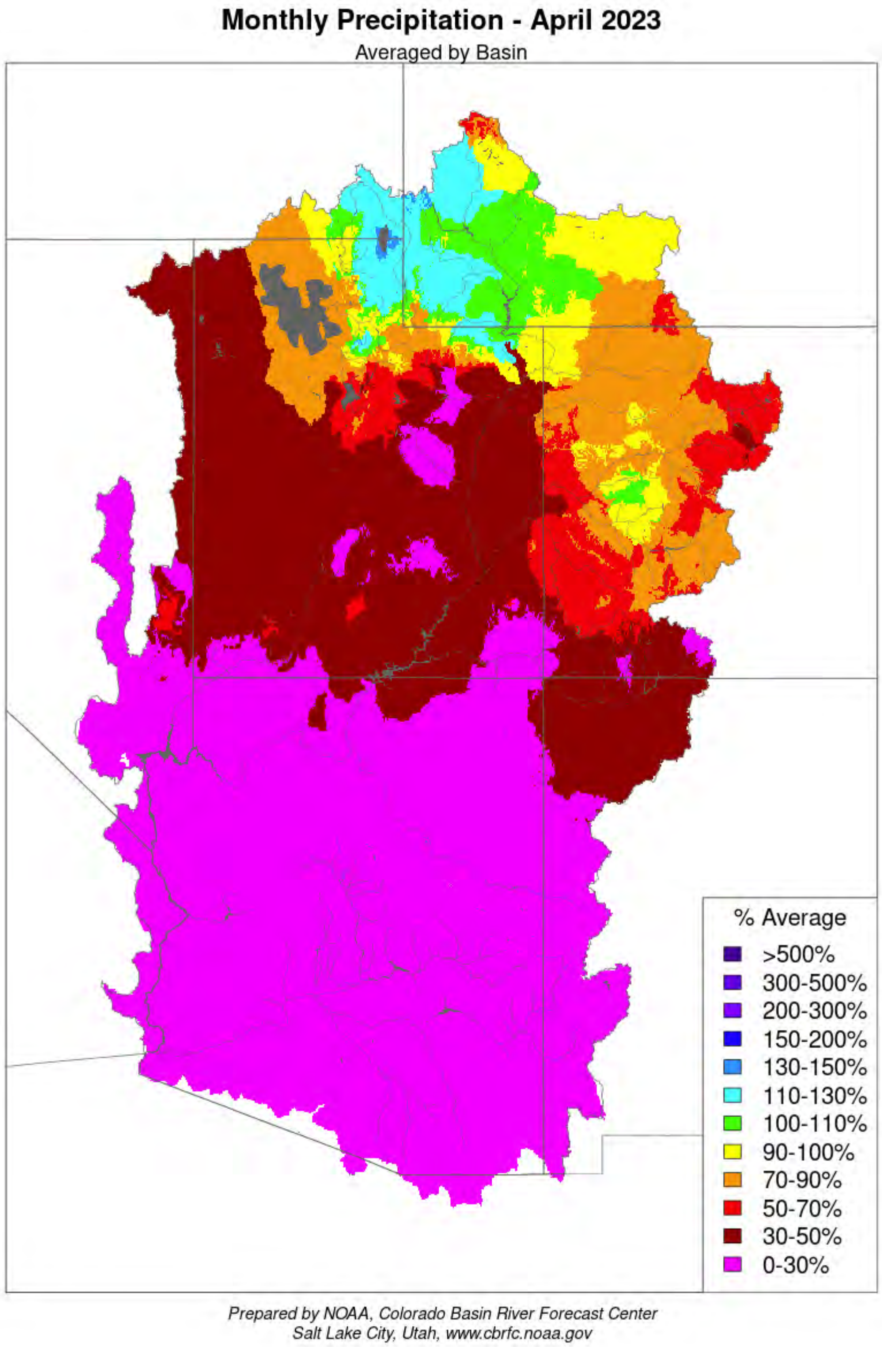


Figure 4.10 **April 2023 precipitation, percent of normal**

5. ASSESSMENT OF SEEDING EFFECTS

5.1 Background

The task of determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program for a particular season is rather difficult. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area and between one area and another during a given season. The ability to detect a seeding effect becomes a function of the magnitude of the seeding increase and the number of seeded events, compared with the natural variability in the precipitation pattern. This can be described as a (seeding effect) signal to noise ratio issue. Larger seeding effects can be detected more easily, and with a smaller number of seeded cases, than are required to detect smaller increases.

Historically, consistently positive results have been observed in wintertime seeding programs in mountainous areas. However, the apparent differences due to seeding are relatively small, usually of the order of a 5-10 percent seasonal increase. In part, this relatively small percentage increase accounts for the significant number of seeded seasons (often ten years or more) required to establish these results for a particular program with any confidence.

Despite the difficulties involved, some techniques are available for estimation of the effects of operational seeding programs. These techniques are not as statistically rigorous as the randomization technique used in research, where roughly half the sample of storm events is randomly left unseeded. However, most of NAWC’s clients do not choose to cut the potential benefits of a cloud seeding project in half in order to better document the effects of the cloud seeding project. The less rigorous techniques can, however, potentially offer a reasonable indication of the long-term effects of seeding on operational programs.

A commonly employed technique, the one utilized by NAWC in this assessment and in evaluation of its other winter seeding projects, is a "target" and "control" comparison. This technique is described by Dr. Arnett Dennis (1980) in his book entitled “Weather Modification by Cloud Seeding”. The technique is based on the selection of a variable that would be affected by seeding (such as precipitation or snowpack). Records of the variable to be tested are acquired for an historical period of many years’ duration (20 years or more if possible). These records are partitioned into those located within the designated "target" area of the project and those from well-correlated "control" sites located well outside of the target area.

Ideally the control sites should be selected in an area meteorologically similar to the target, but one which would be unaffected by the project seeding (or seeding from other adjacent projects). The historical data in both the target and control areas are taken from past years that have **not been subject to cloud seeding activities**. These data are evaluated for the same seasonal period of time (months) as that when the seeding is to be, or has been, conducted. The target and control sets of data for the unseeded seasons are used to develop a mathematical model (typically a linear regression), which predicts the amount of target area natural precipitation, based on precipitation observed in the control area. This mathematical model is then used to analyze the selected variable in years where seeding **did not** occur in the control but **did** occur in the target areas. From the model and available data for the control area, we can predict what would likely have transpired in the target area had no seeding occurred, then compare this to what actually happened in the designated target area. Consistent differences between these predicted and observed values 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 a good historical correlation can be found between target and control area precipitation. Generally, the closer the target and control areas are geographically, and in terms of elevation, the higher the correlation will be. Control areas selected too close to the target, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, a correlation coefficient (r) of 0.90 or better would be considered excellent. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set would be explained by the regression equation used to predict the variable (expected precipitation or snowpack) in the seeded years. An equation indicating perfect correlation would have an r value of 1.0.

Experience has shown that it is virtually impossible to provide a precise assessment of the effectiveness of cloud seeding based on a small number of seeded seasons. However, as the data sample size increases, it becomes possible to provide at least a reasonable estimate of seeding effectiveness.

5.2 Target vs. Control Evaluations – Precipitation and Snowpack Data

The Natural Resources Conservation Service (NRCS) collects data from a number of precipitation and snow measurement sites. Most of these sites have been converted to automated SNOTEL sites in the last 30 years, although manual snow course measurements are still conducted at some locations. NAWC has utilized monthly precipitation and snow data from a number of these sites for use in seeding program evaluations. The number of sites operated by agencies such as the NRCS, especially manual snow course sites, has been gradually reduced. Even some cooperative observer sites, which are managed by the National Weather Service, have been either discontinued or have become inactive. Therefore, the selection of target and control sites first involves examination of the period of record of data at a given location, and changes to the set of target or control sites are sometimes necessary in the event that measurements at a site are discontinued.

There are multiple cloud seeding programs conducted in the State of Utah. As a consequence, potential control areas that are truly unaffected by cloud seeding are somewhat limited in geographic area. This is complicated by the fact that the best correlated control sites are generally those closest to the target area. Many measurement sites in this part of the state, although not located within the boundaries of the intended area of effect of a seeding program, have been subjected to potential effects of numerous historical and current seeding programs. This renders such sites of questionable value for use as control sites. Studies of downwind seeding effects suggest that if we wish to consider any precipitation gauge sites downwind of the seeded area as control sites for the High Uintas project, they should be located at least 50-75 miles downwind of current or historic cloud seeding programs in Utah (or Idaho and Nevada) to avoid significant contamination.

Our normal approach in selecting control sites for a new project is to look for sites upwind or crosswind from the target area that will geographically bracket the intended target area. The reason for this approach is that some winter seasons are dominated by one upper-level wind (jet stream) pattern while other seasons are dominated by other flow patterns. The result of these differing weather patterns and storm tracks often results in heavier precipitation in one area versus the other. For example, a strong El Niño pattern may favor below normal precipitation in one region more than in another. Having control sites on either side of the target area relative to the generalized flow pattern can improve the prediction of target area precipitation under these variable upper air weather patterns.

An additional consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control or target 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 High Uintas program, typically have reliable long-term records with external variables (such as terrain aspect and surrounding vegetation) carefully selected or maintained. The double mass plot is an engineering tool that will indicate any changes in relationships between two stations, and may be particularly useful if one or both stations have moved during their history. If a site exhibits either an abrupt change due to relocation, or long-term trends that differ substantially from other sites in the area, it may be excluded from further consideration.

There are some things to consider when dealing with the two types of precipitation observations typically available from mountainous areas in the west: standpipe storage precipitation gauges and snow pillows. There are some potential problems associated with each type of observation. With the advent of the SNOTEL data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before the SNOTEL system was developed, these data had to be acquired by actually visiting the site to make measurements. This is still required at some sites. Figure 5.1 is a photo of an NRCS SNOTEL site, with labels to allow the reader a better understanding of the two types of observation systems. The vertical tube is the standpipe storage gauge, which is approximately 12" in diameter. The gauges are approximately 20’ in height so that their sampling orifices remain above the snowpack surface. There are at least two types of potential problems associated with high elevation observations of the water equivalent of snowfall, as measured by standpipe precipitation storage gauges. The two areas of concern are clogging at the top of the standpipe storage gauge, and blow-by of snowflakes past the top of the standpipe gauge. Either situation would result in an underestimate of the actual precipitation that fell during such periods. In the fall, the storage gauge is charged with antifreeze, which melts the snow that falls to the bottom of the gauge. A pressure transducer records the weight of the solution. The weight of the antifreeze is subtracted from the total weight, giving the weight of the water, which is then converted into inches. Heavy, wet snow may accumulate around the top of the standpipe storage gauge, either reducing or stopping snow from falling into the standpipe and resulting in an underestimate of precipitation. Snow that falls with moderate to strong winds may blow past the top of the gauge, which can also result in an underestimate of precipitation. NRCS sites are normally located in small clearings in forested areas to help reduce the impacts of wind effects. Sites that are near or above timberline are more likely to be impacted by wind since properly sheltered sites may be difficult to find in these areas. The snow pillow, pictured on the pad at ground level in the foreground of Figure 5.1, is filled with antifreeze. This system weighs the snowpack, providing time-resolved records of the snowpack water content. Snow pillows can also have difficulty in providing accurate measurements of snow water content, because of wind either adding or removing snow from the measurement site when snow conditions are favorable for drifting.

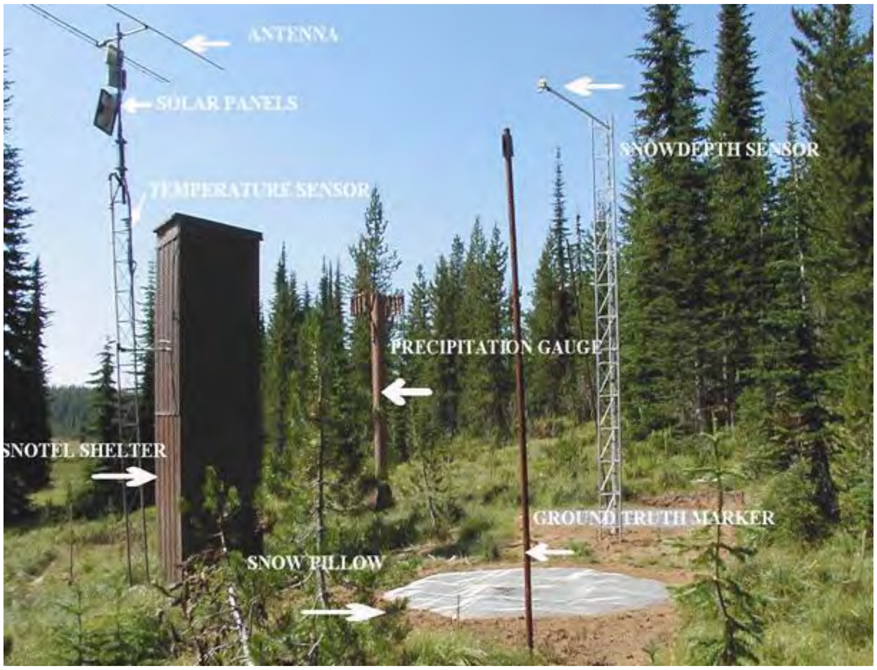


Figure 5.1 **Equipment at a SNOTEL site**

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 to replenish the supply when the snow melt occurs. Hydrologists routinely use snow water content measurements to forecast 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 available for both precipitation and snowpack measurements. Consequently, it is worthwhile to evaluate the effects of seeding on snowpack as well.

There are some potential problems with snow course (manual) type of measurements that must be recognized when using those measurements to evaluate seeding effectiveness. Because not all winter storms are cold, sometimes rain as well as snow falls in the mountains. This can lead to a disparity between precipitation totals which theoretically measure everything that falls, and snowpack water content which measures only the water held in the snowpack. Warm periods can occur between snowstorms. If a significant warm period occurs, some of the precipitation that fell as snow will have melted or sublimated by the time the next snow course measurement is made. Thus, some of it may not be recorded in the snow water content measurements. This can also lead to a greater disparity between the snow water content at higher elevations (where less snow will melt in warm weather) and that observed at lower elevations. The newer daily SNOTEL measurements avoid some of these problems, but depletion of the snowpack can occur even with SNOTEL measurements when dealing with April 1st observations. We are concerned with both types of measurements since we often use snow course measurements to provide a longer historical data base from which the regression equations can be developed. In addition, snowpack measurements are still conducted manually at a few mountain sites up to the present time.

Another factor that can affect the indicated results of the snowpack evaluation is the date on which snow course measurements were made. Since the advent of SNOTEL, data are now available on a daily basis. However, 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, these measurements have been made as many as 5-10 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. Nonetheless, the measurement timing issue can affect the data. Only two manual snow course sites are still used in analysis for this program, both of which are located in the target area.

April 1st snowpack readings have generally become accepted as the conventional data set for evaluating seasonal snowpack water content since they usually approximate 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 five months of seeding are contained in the April 1st snowpack measurements, April 1st was selected as the most appropriate standardized date for snowpack analysis.

The bottom line is that it is difficult to accurately measure snow water equivalent at unmanned high-elevation sites. Both types of NRCS observations (gauge and snow pillow) can best be viewed as approximations of the actual amount of water that falls during a winter season. NRCS SNOTEL sites frequently provide the only type of precipitation observations available from the higher elevation areas targeted by winter cloud seeding programs. They are well-suited for use in estimations of seeding effects, but interpretation of the indicated seeding effects must take into account the limitations of the measurement systems and their data.

5.3 Target vs. Control Evaluations – Streamflow Data

In addition to the precipitation and snow water equivalent data which are used in these evaluations, NAWC has utilized some streamflow data for use in target and control analyses for the High Uintas program. Monthly streamflow data were obtained from the USGS (United States Geological Survey) website for sites that had a long history of unregulated streamflow measurements. Streamflow data can, under the right circumstances, directly address the issue of how much additional water is being produced by a seeding program. There are some potential difficulties here as well, including diversions for irrigation (which are present to some extent above even most of the “unregulated” sites), and significant carryover in soil moisture and resultant streamflow from one season to another, which lowers the correlation between target and control sites. Overall, the best correlation between control and target sites is found with the precipitation data, followed by snow water equivalent, with streamflow correlations generally having the lowest correlation of the three data types.

5.4 Evaluation Methodology

Using the target-control approach introduced in the Section 5.1, the mathematical relationships for two variables (precipitation and snowpack) were determined between a group of sites in an unseeded area (the control group) and the sites in the seeded area (the target group), based upon records for a common period prior to any seeding in either area. From these data, mathematical models were developed whereby the amount of precipitation or snowpack observed in the unseeded (control) area was used to predict the amount of natural precipitation in the seeded (target) area. This "predicted" value is the amount of precipitation or snowpack that would be expected in the target area without seeding. The difference between the predicted amount and the observed amount in the target area is the excess, which may be the result of cloud seeding. Statistical tests have shown that such indications have little statistical significance for individual seasons, and usually fall within the standard deviation of the natural variability. However, more meaningful estimates can be obtained by combining the results of several or more seeded seasons.

5.5 Target and Control Sites - Precipitation

Precipitation measurements were available from six sites within the target area, the same sites as used in the previous several years. There are additional SNOTEL sites in the target area (e.g., Chepeta), but they have shorter periods of record. Thus, they were not considered in this analysis. The sites selected for use in the evaluation work are shown in Figure 5.2, and are all higher elevation NRCS sites. The average elevation for the target area sites is 9,875 feet above mean sea level (MSL). Specifics in regard to location and elevation of these six target area sites are provided in Table 5-1.

For many years, winter cloud seeding in Utah was limited to mainly the central and southern portions of the State, although occasional winter seeding was conducted in the mountains of Tooele County (southwest of the Salt Lake City area) in the late 1970's and early 1980's. However, beginning in the 1988 water year, winter cloud seeding programs became more widespread in northern Utah. The result of this increase in cloud seeding projects is that it has become more difficult to locate control areas that have not been affected by other cloud seeding programs. Also, some (non-SNOTEL) precipitation gage sites used as controls no longer have ongoing data collection.

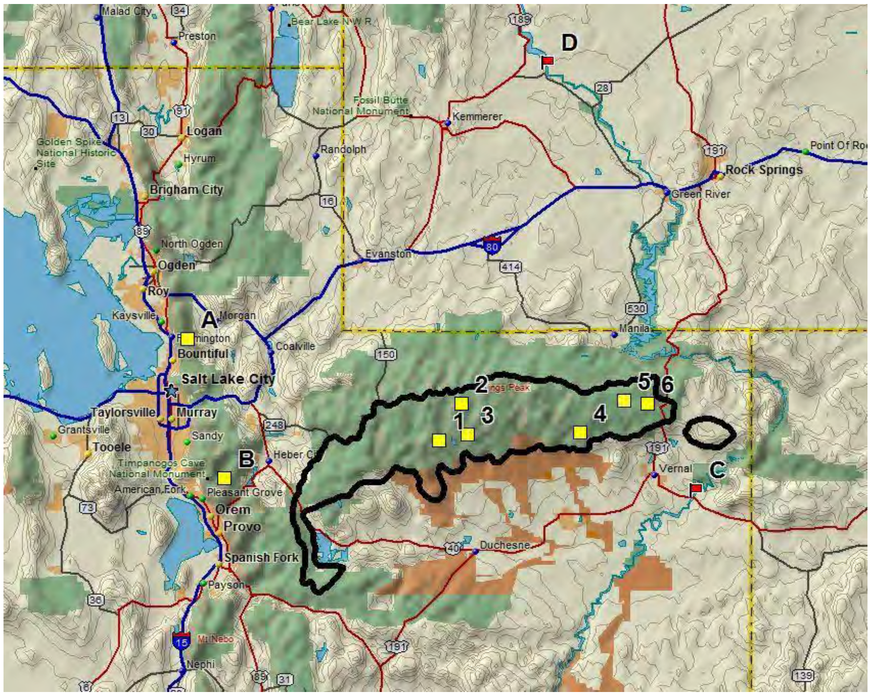


Figure 5.2 **Precipitation gauges used as target area sites (number ID's) and control sites (letter ID's). The yellow boxes represent SNOTEL locations and the flag is an NWS co-op site.**

The control gauge sites used in the evaluations were carefully selected according to the following criteria: 1) similarity to the target area sites, in terms of elevation and meteorology; 2) geographic bracketing of the target area; and 3) mathematical correlation of the data with that in the target area. The Strawberry Divide SNOTEL site was at one time included in the control group, but has been excluded from evaluations in recent years since it is now in part of the target area. Two cooperative (valley) reporting gauges, located at Heber and Vernal, were previously used as control sites, but have been discontinued because data are no longer available at these sites. The relationship of the control area gauges to the target area is shown in Figure 5.2, and the specifics in regard to the locations and elevations of the control sites are provided in Table 5-1.

Table 5-1
Control and Target Area Precipitation Gauge Sites

Group ID	Site Name	Site Number	Elevation (feet)	Latitude (N)	Longitude (W)
Control					
A	Farmington Canyon Upper	11J11S	8000	40°58'	111°48'
B	Timpanogos Divide	11J21S	8140	40°26'	111°37'
C	Jensen	424342	4750	40°22'	109°21'
D	Fontenelle Dam, WY	483396	6480	41°59'	110°04'
Target					
1	Brown Duck	10J30S	10600	40°35'	110°35'
2	Five Points Lake	10J26S	10920	40°43'	110°28'
3	Lakefork #1	10J10S	10100	40°36'	110°26'
4	Mosby Mountain	09J05S	9500	40°37'	109°53'
5	Trout Creek	09J16S	9400	40°44'	109°40'
6	King’s Cabin	09J01S	8730	40°43'	109°33'

It is recognized that the group of control sites in Table 5-1 might provide a conservative estimate of the effects of seeding for the High Uintas, since there could have been some seeding effects impacting some of the control sites (e.g. seeding from the Western Uintas and Six Creeks programs could impact the precipitation at Heber, and seeding in eastern Tooele County and in Box Elder County could impact sites like Farmington Canyon). Those impacts would have the effect of raising the predicted target area precipitation and, thus, lowering the indicated effects of seeding in the High Uintas target area. The average elevation of all seven control sites is 6,842 feet, which is much lower than that of the target sites (9,875 feet). The large elevation difference is due in part to the fact that the Uinta Range is the highest mountain range in the region, and most other high elevation sites are in areas with other seeding programs. The locations of the control sites are shown in Figure 5.2. Elevation differences are important in snow water content evaluations because snowmelt may impact high and low elevation sites differently. The great elevation difference between the target and control sites is also of significance in the precipitation evaluations because of the potential for much windier exposures at the Uintas sites which are ~3,000 feet higher on average than the control sites. Gauge catch deficiency due to wind can be very significant in more exposed areas, as can the problem of drifting snow.

5.6 Target and Control Sites - Snowpack

The procedure was essentially the same as was done for the precipitation evaluation, e.g., control and target area sites were selected, and average values for each were determined from the historical snowpack data. Due to concerns regarding potential contamination by other seeding projects, combined with some period of record limitations and consideration of site correlation values, a short 13-year historical period (1975-88) was used in most of the snow water content evaluations. The limited amount of historical data renders the equations using the historical regression technique questionable, as described in the earlier precipitation evaluation section. Historical periods of at least 20 seasons duration are very desirable when utilizing this technique. The years after the 1988 water year were excluded from the historical period in most of these evaluations, given a number of seeding programs in northern Utah beginning with the 1989 water year, especially along the Wasatch Range west of the Uintas.

Four sites were selected as controls for the snowpack evaluation. The control group provides reasonably good correlations with the six-site target area group. The six snowpack target sites include four of the six sites used in the precipitation evaluations (data were unavailable back to 1975 for the Brown Duck and Five Points Lake sites), plus two additional manual snow course sites (Lakefork Mountain #3 and Spirit Lake). Spirit Lake is actually located on the north slope of the Uintas but is very close to the crest, so we believe it to be representative of the original target area in general (and now within the target area, with the additional of the northern slope to the program). It should also be noted here that SNOTEL sites were installed in 2009 at the Lakefork Mountain #3 and Spirit Lake snow course locations, and data at these sites became SNOTEL-only (instead of snow course) beginning in 2011. The target and control area snow course/snow pillow site names, elevations and locations are summarized in Table 5-2, and site locations are shown in Fig. 5.3. The elevations of the control area sites averaged 8,184 feet. The target sites were significantly higher, averaging 9,405 feet. The relationship of the control area snowpack sites to the target area is shown in Figure 5.3.

Due to the challenges involved in the target/control analyses for the High Uintas program, including concern over short historical periods, a snow water content regression (linear and multiple linear) that uses fewer sites but a much longer historical regression period of 46 years was also conducted.

Table 5-2
Control and Target Snowpack Sites

Group ID	Site Name	Site Number	Elevation (feet)	Latitude (N)	Longitude (W)
Control					
A	Farmington Canyon	11J11S	8000	40°58'	111°48'
B	Lookout Peak	11J64S	8200	40°50'	111°43'
C	Timpanogos Divide	11J21S	8140	40°26'	111°37'
D	Kelley RS, WY	10G12S	8180	42°15'	110°48'
Target					
1	Lakefork #1	10J10S	10100	40°36'	110°26'
2	Lakefork Mountain #3	10J12S	8400	40°33'	110°21'
3	Spirit Lake	10J55S	10300	40°50'	110°00'
4	Mosby Mountain	09J05S	9500	40°37'	109°53'
5	Trout Creek	09J16S	9400	40°44'	109°40'
6	King's Cabin	09J01S	8730	40°43'	109°33'

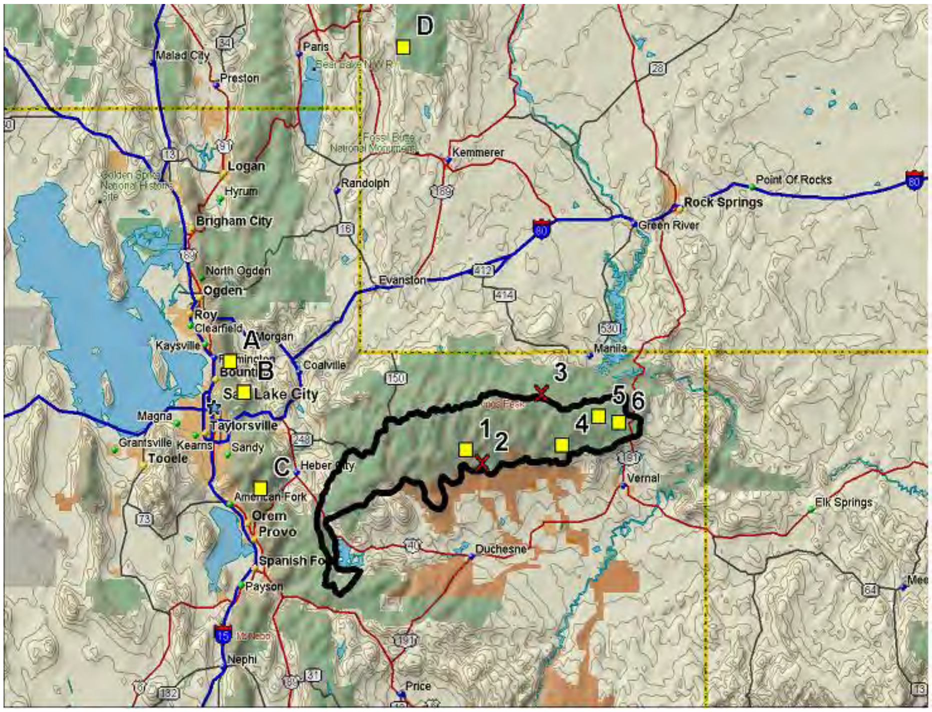


Figure 5.3 Target sites (numbered) and control area snow sites (letters); squares are SNOTEL sites, and X's are snow courses

5.7 Target and Control Sites - Streamflow

NAWC has investigated numerous target/control type evaluation techniques, as well as multiple variations of existing techniques, in an attempt to provide the client with a reasonable estimate of precipitation increases resulting from the seeding program. One of these techniques is an evaluation based on March – July streamflow, utilizing several control sites that had essentially unregulated streamflow records. Three suitable control sites were located in western Wyoming, and two sites were similarly located in northwestern Colorado. Three suitable (unregulated) streamflow gauges were used to represent target area runoff (Yellowstone, Lake Fork and Ashley Creek drainages). Streamflow data at these sites have longer periods of record than SNOTEL snow and precipitation data, yielding a longer historical base period. The sites utilized in these streamflow comparisons have data back to at least 1964, allowing a 30 year base period to be established for the period prior to the beginning of the South Slope seeding program (certain years were excluded from the base period due to a historical seeding program affecting western Wyoming). There were two separate regions with unregulated streamflow gauges that were judged to be suitable for controls. One of these groups is in western Wyoming. Examination of the correlation between these and the target area sites, along with examination of double-mass plots, an engineering tool used to examine the consistency of an historical paired data set, resulted in three of these Wyoming gauges being selected as controls. Similarly, two control sites were selected from an available set in northwestern Colorado, which are unlikely to be affected by current or historical seeding programs. These sites are listed in Table 5-3, and shown on the map in Figure 5.4.

Table 5-3 Control and Target Streamflow Gauges
(Data obtained from the USGS website)

Group ID	Site Name	USGS Site Number	Latitude (N)	Longitude (W)
Control - Wyoming and Colorado				
A	Hams Fork, WY	09223000	42°07’	110°42’
B	Smith’s Fork, WY	10032000	42°03’	110°24’
C	Fontenelle Creek, WY	09210500	42°06’	110°25’
D	Little Snake River, CO	09260000	40°33’	108°25’
E	White River	09304500	40°02’	107°51’
Target - Utah				
1	Lake Fork	09289500	40°36’	110°32’
2	Yellowstone River	09292500	40°31’	110°20’
3	Ashley Creek	09266500	40°35’	109°37’

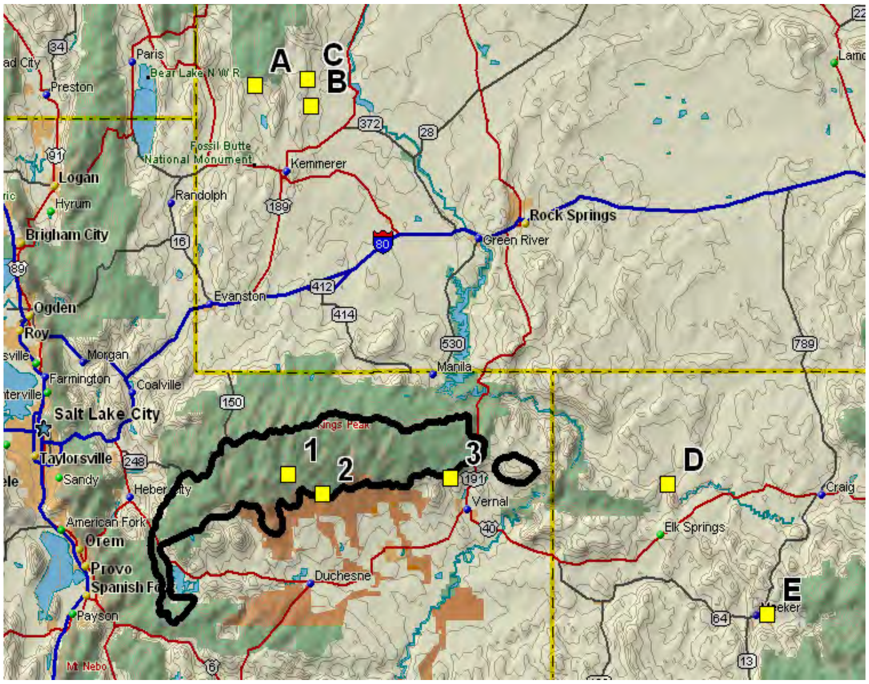


Figure 5.4 **High Uintas streamflow target and control gauges**

Over the course of this seeding program, several evaluation methods have been applied to the precipitation, snowpack and streamflow data. The results of the various evaluations are summarized in the following sub-sections, and Appendix C contains more detailed information for some of these evaluations.

5.8 Development of Regression Equations

NAWC compared various methods of analyzing the data, including the linear and multiple linear regression methods which have been used with this and similar programs. The target and control site historical (non-seeded) data for precipitation, snowpack, and streamflow were used to develop regression equations that describe the relationship between the control and target areas in the absence of cloud seeding. In the precipitation evaluation, for example, the monthly precipitation values were totaled at each gauge in the control and target areas for the December-April periods in each of the historical (not seeded) water years from 1980 - 1988, 1994, and 1996-2000, for a total of 15 seasons. The reasons for the short historical period are a) a lack of consistent precipitation measurements prior to the advent of the SNOTEL observations and b) the necessity of excluding winter seasons in which there were some seeding activities conducted in upwind areas that may have impacted precipitation in the High Uintas target area (e.g., projects in the western Uintas or the Wasatch Front area). Averages for each group were obtained, and predictor equations developed from these data for a five-month period (December through April). Appendix B contains details regarding some of the historical regression relationships that have been developed and applied to the seeded seasons.

Development of snowpack and streamflow regressions was similar. The snowpack analyses were based on snow water equivalent amounts measured on April 1st (using both the SNOTEL and snow course measurements). April 1st is important because it approximates the total seasonal snowpack accumulation fairly well in many areas, usually before significant melting begins. Also, many water supply forecasts are based on April 1 snow water content. The streamflow analysis utilized total streamflow (in acre-feet) during the March – July period. This period has been found to be one of the best correlated with winter season precipitation. April – July streamflow can be used for this as well, although the runoff can begin during March in some seasons, especially areas on a southerly exposure such as the southern slopes of the Uintas. The primary snowpack regression used for this program was based on only 13 historical seasons (water years 1975 – 1987), although an alternate snowpack regression that was also developed utilized long-term historical data available at only a small number of sites to produce a 46-year historical period. The streamflow regression was based on a fairly long historical period of 30 seasons. These include water years 1966, 1971-79, and 1983-2002. The historical regression periods were selected on the basis of data availability and avoidance of seasons where historical seeding programs would have directly impacted some or all of the control sites.

Multiple regression analyses relate each control site individually to the average of the target area sites, and these were conducted as well. This multiple regression analysis method was used because it provides a higher correlation between control and target sites, which can yield a better estimate of seeding effects if there is sufficient historical (non-seeded) data for a meaningful regression equation to be established using this method. For the precipitation and snowpack evaluations, a relatively short historical period makes this type of analysis somewhat questionable since the number of independent variables (control sites) in the equation becomes relatively large in comparison to seasons in the historical period. The results of the multiple regression analysis (for precipitation and snowpack) were still considered, but for this program the multiple regression method is better suited to the streamflow data set which has a much longer historical period.

5.9 Evaluation Results

Precipitation evaluation results have been examined for a period of 21 seeded seasons (2003-2023 water years). The seeded period used in one snowpack evaluation (with more sites but a short historical period) excludes the water year 2004, 2007, 2012, and 2015 seasons due to early melting in those years, and so includes only 15 seasons. The other long-term snowpack evaluation (few sites but 46 historical seasons) excludes these same seeded seasons due to early snow melt. This evaluation originally had three control sites but one snow course (White River #3) appears to have been discontinued in 2016 so the regression equation was re-established without this site. The streamflow evaluation currently has data available through 2022 for the March – July seasonal period, and so includes the 2003-2022 water years, for a total of 20 seasons.

The evaluation techniques as described yield an estimation of the observed/predicted amount of precipitation, snow water content, or streamflow for an individual season. Individual season results are included in the tables in Appendix B, in the “RATIO” column for the seeded seasons. Results for the current season are discussed below Table 5-4. A ratio of 1.05, for example, would suggest a 5% increase over the natural precipitation, snowpack, or streamflow predicted for the target area based on the historical regression equation. A ratio at or below 1.0 is not indicative of an increase over the natural precipitation or snowfall. An increase for an individual seeded season or combination of seeded seasons could be attributed to seeding effects. However, it is important to exercise caution in interpreting single-season statistical indications, since the natural variability of weather patterns between control and target areas will often outweigh the effects of seeding in a given year. This natural variability can result in a false or exaggerated positive indication, or in a low ratio (lack of indicated effects) when seeded effects were actually present. The strength of this type of evaluation is in multi-season indications over many seeded years.

Table 5-4
Summary of High Uintas Evaluation Results

Evaluation Type	Method	Pre-Seeded Years	Seeded Years	Correlation (R-value)	Resultant Ratio
April 1 Snow Water Content	Linear Regression	13	16*	0.81	0.97
April 1 Snow Water Content	Multiple Linear	13	16*	0.94	1.02
April 1 Snow Water Content	Linear Regression	46	16*	0.83	1.04
April 1 Snow Water Content	Multiple Linear	46	16*	0.86	1.10
Dec – Apr Precipitation	Linear Regression	15	20	0.86	0.96
Dec – Apr Precipitation	Multiple Linear	15	20	0.92	0.95

* Snowpack result excludes 2004, 2007, 2012, and 2015 due to early snow melt

** Streamflow evaluation includes seeded year data up through 2022, as the full March – July streamflow data for the current season is not yet available

Overall, indications from the various evaluation methodologies (linear regression and multiple linear regression) were mixed. Appendix B contains detailed evaluation results. Overall, a majority of these observed/predicted ratios were in the 0.95 - 1.10 range, particularly for the evaluations that exhibit more stable mathematical characteristics (i.e. evaluations of December – April precipitation and snow water content). Correlation (expressed as R-values) was generally highest for the precipitation evaluations, somewhat lower for the snowpack evaluations, and lowest for the various streamflow evaluations. Relatively low correlations (R values of much less than perhaps 0.85) indicate that there is considerable natural variability between the control and target areas, which for the South Slope of the Uintas target area is essentially unavoidable given its uniqueness in terms of meteorology, climatology and barrier orientation. Development and performance of the regression equations are greatly affected by the duration of the historic period; longer base periods are highly desirable. Because of this factor, NAWC included a long-term snowpack evaluation, as mentioned earlier, using a base period of 46 seasons and a limited number of target/control sites with long records, sites that are also unlikely to be affected by surrounding seeding programs. The results of this particular evaluation (ratios of 1.03 for the linear and 1.09 for the multiple linear, for the average of the seeded seasons) are suggestive of snowpack increases during the seeded seasons for the High Uintas seeding program. Snowpack evaluations were not meaningful for the 2004, 2007, 2012 and 2015 seasons due to substantial early snowmelt and those seasons were excluded from the snowpack evaluation results.

With regard to the streamflow data, it is apparent in the data that not only are the correlations fairly poor, but there appears to be a good deal of non-linearity that produces better evaluations results (in general) during wetter years. This is likely due to higher inter-annual variability in the target area than the control areas. Its is also observed that the seeded seasons were generally drier as a whole, on the order of 10% less runoff, than the historical seasons across the entire region (both target and control). Thus, the seeded season results have likely been biased toward lower ratios given the overall dryness of these seasons.

It is important to recall that, for the High Uintas program, there are a number of factors that make a meaningful analysis of the seeding effects difficult. These include the following: a) a relatively small number of seeded seasons, b) high seasonal variability between control and target areas, c) generally short historical periods without seeding from which regression equations can be developed, d) potential impacts on the historical regression equations from other NAWC winter seeding programs, e) sensitivity to early snowmelt issues at south-slope locations, and f) the possible long-term reduction of precipitation in the target area due to pollution as documented for precipitation sites slightly west of the High Uintas target area (Griffith et al., 2005). Items b) and d) above are described more fully in sections below.

5.10 Seasonal Variability, Related to Storm Track and Barrier Orientation (item b)

From a meteorological standpoint, there are several possible reasons why target area precipitation was comparatively low on average during the seeding seasons compared to that observed in various control areas. The El Nino/La Nina phase and various other factors can affect the location and orientation of the primary storm track on a seasonal and multi-seasonal basis. This can lead to large (either negative or positive) precipitation anomalies in the High Uintas in comparison to the surrounding region, especially given the east-west orientation of the mountain barrier. Storm events that are accompanied by a wind pattern moving essentially straight west to east, i.e., basically barrier-parallel can present reasonable seeding opportunity for the target area, although base (natural) amount of precipitation falling in the High Uintas with this type of flow pattern is low compared to surrounding areas. The predominantly north-south oriented mountain barriers in the intermountain region produce strong orographic (terrain-induced) lift in westerly air flow situations, while the west-east oriented Uinta Range produces minimal lift in those situations. The result is a minimal orographic component of the precipitation in the Uintas during periods of westerly flow. Given that the orographic component of precipitation is high in the mountains of Utah, approaching 75% of the winter precipitation in many areas, a dominant wind pattern that is even slightly anomalous can lead to a negative precipitation anomaly that may more than offset the actual seeding effects. In addition, there are indications that large, closed-circulation storm systems (so-called cutoff lows) during the spring, which climatologically contribute a substantial amount of snowfall over the Uinta Range particularly during the month of April, were relatively lacking during many of the seeded seasons. The effect of that sort of natural variation can easily mask positive seeding effects.

5.11 Impacts from Other Seeding Projects (item d)

Other seeding programs being conducted in Utah may be impacting the apparent effects of seeding in the High Uintas. For example, the programs conducted in Tooele County and Box Elder County (which included seeding in both western and eastern portions of the county last winter) may be increasing the precipitation at some of the northern control sites (e.g., Farmington Canyon) and seeding in Juab and Sanpete Counties could be increasing precipitation at some of the southern control sites (e.g., Timpanogos Divide and Heber). Some of the Uinta program SNOTEL sites are within approximately 50 miles downwind of other seeding programs. Solak et al. (2003) reported that precipitation appears to have been increased at similar downwind distances due to the cloud seeding program being conducted in central and southern Utah, with similar results in a subsequent analysis up through 2018. For the High Uintas precipitation evaluation, 15 historical seasons were selected which exclude Water Years 1989 through 2002 since a number of seeding programs began in WY 1988 or 1989 in northern Utah, especially along the Wasatch Range west (upwind) of the Uintas. These seasons were excluded from the historical period due to potential contamination effects. Similar exclusions resulted in a 13-year historical data set for the snowpack evaluation, while the streamflow evaluation had a different set of historical seasons (during the 1970s and early 1980s) excluded because of the Bear River seeding program affecting portions of western Wyoming where some of the streamflow control sites are located.

In order to illustrate the potential effects of contamination, assume that the average precipitation at the control sites was increased by 5% due to seeding from other programs. This would also raise the predicted target area precipitation by roughly 5%. **If** this were the case, it would cause a similar 5% precipitation increase in the High Uintas target area to be undetected in a more basic mathematical analysis. A final (and very important) consideration in the estimation of seeding effects for this program pertains to the results obtained from numerous similar programs in Utah and elsewhere in the western U.S. While each program is unique, evaluation results from most of these programs have ranged from approximately 5-10% increases over the estimated natural seasonal precipitation.

5.12 The Bottom Line

With consideration given to the meteorology and physiography of the Uintas, the range of results of various evaluations of seeding effects, the peculiarities of the seeded period, and results of similar programs, our best estimate is that the High Uintas seeding program has increased the project target area precipitation by approximately 3-5% on average during the seeded seasons. Table 5-4 summarizes the results of the various evaluations conducted to date for the High Uintas program. Detailed data from these evaluations are shown in Appendix C.

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APPENDIX A: SUSPENSION CRITERIA

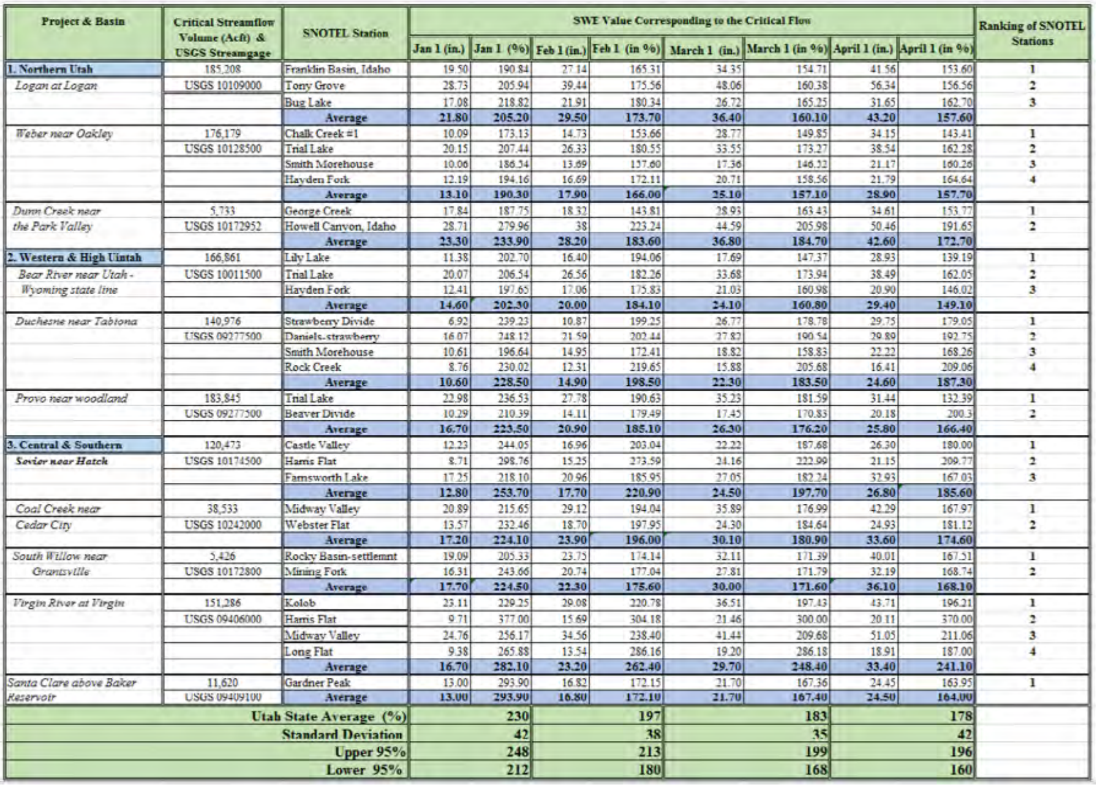
Certain situations require temporary or longer-term suspension of cloud seeding activities, with reference to well-considered criteria for consideration of possible suspensions, to minimize either an actual or apparent contribution of seeding to a potentially hazardous situation. The ability to forecast (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

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	5,733	George Creek	17.84	187.75	18.32	143.81	28.93	163.43	34.61	153.77	1
the Park Valley	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	29.80	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	38,533	Midway Valley	20.89	215.65	29.12	194.04	35.89	176.99	42.29	167.97	1
Cedar City	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 High Uintas Program, SNOTEL sites including Lily Lake, Trial Lake, Hayden Fork, Strawberry Divide, Daniels-Strawberry, 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.

Rain-induced Winter Floods

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

Severe Weather

During periods of hazardous weather associated with both winter orographic and convective precipitation systems it is sometimes necessary or advisable for the National Weather Service (NWS) to issue special weather bulletins advising the public of the weather phenomena and the attendant hazards. Each phenomenon is described in terms of criteria used by the NWS in issuing special weather bulletins. Those 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 Warning - This is issued by the NWS when flash flooding is imminent or in progress. In the Intermountain West, these warnings are generally issued relative to, but are not limited to, fall or spring convective systems.

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, 2022-2023

Table B-1
Generator Hours for High Uintas Program, 2022-2023, Storms 1-10 (rounded to quarter hour)

Storm	1*	2*	3*	4	5	6	7	8	9	10
Dates	Nov 3	Nov 9-10	Nov 28-29	Dec 12-13	Dec 15	Dec 21	Dec 27-28	Dec 31-Jan 2	Jan 6	Jan 10-11
SITES										
HU1			17					40		7
HU2				27		8.25	22	6.5		
HU3										
HU4										
HU5		15		14			11			12
HU6		15		14			11			12
HU7		12		21			17.5	14.5		
HU8		12		21.25			17.5	15		
HU9**				18			16.5	20		
HU10	7.25				9					
HU11	8.25				9					
HU12										
HU13		12		24.25				16.5		
HU14		12								
HU15										13
HU16		8.75								
HU17	6.5			23.5						
HU18	8.25									
HU19	7.25				9					
HU20	8				9					
HU22										
WU3										
WU4										
WU6										
WU7			21							
WU8			21							
WU9		12	21							
WU10			21							
WU11					1.75					
WU12			17.25		9				9	
									9	
Storm Total	**41.5**	**98.75**	**118.25**	**145**	**46.75**	**8.25**	**79**	**54.5**	**18**	**44**

*Seeding for Lower Basin Extension

** HU9 is a remotely operated site with higher output, hours are counted separately

Table B-2
Generator Hours for High Uintas Program, 2022-2023, Storms 11-20

Storm	11	12	13	14	15	16	17	18	19	20
Dates	Jan 14-15	Jan 16-18	Jan 27-28	Jan 29	Feb 5	Feb 6	Feb 8	Feb 21-22	Feb 27-28	Mar 4-5
SITES										
HU1					5.75			7	12	15
HU2	8		20					7	14	15
HU3		17.5					5.75			
HU4		17.5				3.25	5			
HU5	12	11.5						19	13	15
HU6	12	11.5						19	13	15
HU7	23			9				21		18
HU8	23			9.25				20.75		19
HU9**								20.75		
HU10							5			
HU11										
HU12										
HU13	22.75							17.25		
HU14								16.75		
HU15										
HU16										
HU17		10.5					5			
HU18		17.5					5			
HU19		17								
HU20		17								
HU22										
WU3										
WU4										
WU5										
WU6										
WU7										
WU8										
WU9			20.75							
WU10			20.75							
WU11										
WU12										
Storm Total	**100.75**	**120**	**61.5**	**18.25**	**5.75**	**3.258**	**25.75**	**127.25**	**52**	**97**

** HU9 is a remotely operated site with higher output, hours are counted separately

Table B-3
Generator Hours for High Uintas Program, 2022-2023, Storms 21-31

Storm	21	22	23	24	25	26	27	28	29	30	31
Dates	Mar 5-6	Mar 8	Mar 12	Mar 15	Mar 20	Mar 22	Mar 24	Mar 29-31	Apr 3-4	Apr 20	Apr 24-25
SITES											
HU1	14		2.5	6							
HU2			5	6	8	7.25		22.5			
HU3									25.75	7.25	7.75
HU4											
HU5		4				7					
HU6		4			5			17			5
HU7						12.25					
HU8						12					
HU9		5				12					
HU10											16.25
HU11									32.25		
HU12	12					15		17			
HU13	12					11.25					
HU14						11.25		17			
HU15						9.5		18			
HU16						9		18			
HU17									19.25		
HU18											16.75
HU19											
HU20									32.5		
HU22											
WU3										7.5	
WU4							9.75			7.5	
WU5							9.75	8			
WU6											
WU7											
WU8											
WU9											
WU10											
WU11			5								
WU12			5				9.75	20.5			
Storm Total	**38**	**8**	**17.5**	**12**	**13**	**94.5**	**38.5**	**162**	**109.75**	**22.25**	**45.75**

APPENDIX C: EVALUATION DATA

Summary of High Uintas Evaluation Results

Evaluation Type	Method	Pre-Seeded Years	Seeded Years	Correlation (R-value)	Resultant Ratio
Dec – Apr Precipitation	Linear Regression	15	21	0.86	0.96
Dec – Apr Precipitation	Multiple Linear	15	21	0.92	0.95
April 1 Snow Water Content	Linear Regression	13	17*	0.81	0.97
April 1 Snow Water Content	Multiple Linear	13	17*	0.94	1.02
April 1 Snow Water Content	Linear Regression	46	17*	0.83	1.04
April 1 Snow Water Content	Multiple Linear	46	17*	0.86	1.10
March – July Streamflow 5 control 3 target	Linear Regression	30	20**	0.75	0.99
March – July Streamflow 5 control 3 target	Multiple Linear	30	20**	0.79	0.98
March – July Streamflow 3 control 3 target	Linear Regression	30	20**	0.61	0.95
March – July Streamflow 3 control 3 target	Multiple Linear	30	20**	0.63	0.93

* Snowpack result excludes 2004, 2007, 2012, and 2015 due to early snow melt

** Streamflow evaluation includes seeded year data up through 2022, as the full March – July streamflow data for the current season is not yet available

APPENDIX D: DETAILED EVALUATION DATA AND RESULTS

High Uintas December – April Precipitation, Linear Regression

Regression (non-seeded) period:

Water Year	Control Avg	Target Avg
1980	18.72	17.28
1981	11.03	9.75
1982	21.05	15.50
1983	16.37	13.12
1984	16.62	11.72
1985	10.70	11.50
1986	19.81	16.13
1987	7.85	9.78
1988	8.81	9.33
1994	12.22	10.95
1996	16.21	14.15
1997	18.09	16.83
1998	17.68	14.43
1999	14.03	15.32
2000	13.93	13.63
Mean	14.87	13.30

Seeded period:

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
1989*	12.17	11.05	11.77	0.94	-0.72
1990*	10.68	13.47	10.92	1.23	2.54
1991*	12.21	11.62	11.79	0.99	-0.17
1992*	6.25	7.15	8.42	0.85	-1.27
1993*	15.77	16.45	13.80	1.19	2.65
1995*	15.80	15.15	13.82	1.10	1.33
2001*	12.27	13.93	11.83	1.18	2.11
2002*	11.15	7.83	11.19	0.70	-3.36
2003	9.32	9.40	10.16	0.93	-0.76
2004	13.84	12.15	12.71	0.96	-0.56
2005	18.91	17.20	15.57	1.10	1.63
2006	19.23	14.73	15.76	0.93	-1.02
2007	9.42	8.45	10.22	0.83	-1.77
2008	15.29	13.22	13.53	0.98	-0.31
2009	17.46	13.67	14.76	0.93	-1.09
2010	13.15	12.08	12.32	0.98	-0.24
2011	21.95	17.23	17.29	1.00	-0.06
2012	9.48	8.23	10.25	0.80	-2.02
2013	9.84	10.68	10.45	1.02	0.23
Water Year	**Control Avg**	**Target Avg**	**Predicted**	**Ratio**	**Increase**
2014	11.57	9.83	11.43	0.86	-1.60

2015	8.56	7.20	9.73	0.74	-2.53
2016	14.27	12.27	12.95	0.95	-0.69
2017	23.26	20.63	18.03	1.14	2.60
2019	19.35	16.17	15.82	1.02	0.35
2020	11.30	10.58	11.28	0.94	-0.69
2021	10.11	9.62	10.60	0.91	-0.99
2022	10.11	11.25	10.61	1.06	0.64
2023	25.25	20.53	19.16	1.07	1.38
Seeded Mean	14.35	12.55	13.00	**0.97**	**-0.44**

* Seeding conducted in nearby areas but not in target area

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.858476
R Square	0.736981
Adjusted R Square	0.716749
Standard Error	1.417657
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	73.20731	73.20731	36.42607	4.2E-05
Residual	13	26.12676	2.009751		
Total	14	99.33406			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	4.895582	1.439077	3.40189	0.004725	1.786645
X Variable 1	0.564797	0.093581	6.035401	4.2E-05	0.362628

High Uintas December – April Precipitation, Multiple Linear Regression

Regression (non-seeded) period:

Water Yr	Timp Div	Farm Cyn	Jensen	Font Dam	Target avg
1980	30.4	37.9	4.0	2.6	17.3
1981	18.3	21.0	2.8	2.1	9.8
1982	34.6	45.3	2.5	1.8	15.5
1983	22.5	36.6	3.5	2.8	13.1
1984	20.6	40.8	2.5	2.6	11.7
1985	18.9	19.6	3.4	0.9	11.5
1986	30.5	41.9	3.8	3.1	16.1
1987	10.6	16.8	2.4	1.6	9.8
1988	11.8	18.8	3.2	1.4	9.3
1994	18.8	27.2	1.7	1.2	11.0
1996	24.6	35.9	2.3	2.0	14.2
1997	28.0	37.6	4.0	2.7	16.8
1998	24.8	39.3	3.6	3.1	14.4
1999	18.9	30.1	3.8	3.4	15.3
2000	20.4	31.2	2.9	1.3	13.6
Mean	22.2	32.0	3.1	2.2	13.3

Seeded period:

Water Year	Timp Div	Farm Cyn	Jensen	Font Dam	Target avg	Predicted	Ratio	Increase
1989*	17.7	28.5	1.6	0.9	11.1	10.1	1.10	1.0
1990*	20.8	18.3	2.6	1.0	13.5	11.4	1.18	2.0
1991*	17.2	26.7	3.2	1.7	11.6	12.0	0.97	-0.4
1992*	9.2	13.0	1.8	1.0	7.2	7.6	0.94	-0.5
1993*	25.3	29.9	5.7	2.2	16.5	17.0	0.97	-0.6
1995*	25.3	32.2	2.9	2.8	15.2	13.9	1.09	1.2
2001*	16.9	28.1	2.1	2.0	13.9	10.7	1.30	3.2
2002*	13.3	28.2	1.2	1.9	7.8	8.7	0.90	-0.9
2003	11.0	21.8	2.7	1.8	9.4	9.7	0.97	-0.3
2004	17.6	32.0	2.3	3.4	12.2	11.6	1.05	0.6
2005	33.1	34.4	4.0	4.1	17.2	17.3	0.99	-0.1
2006	29.3	43.6	2.2	1.8	14.7	14.4	1.02	0.4
2007	12.8	20.8	2.8	1.3	8.5	10.1	0.83	-1.7
2008	21.4	33.5	4.6	1.6	13.2	15.0	0.88	-1.8
2009	25.7	38.1	4.4	1.7	13.7	15.9	0.86	-2.2
2010	21.5	25.0	3.9	2.2	12.1	13.8	0.88	-1.7
2011	36.0	45.5	4.4	1.8	17.2	18.7	0.92	-1.4

Water Year	Timp Div	Farm Cyn	Jensen	Font Dam	Target avg	Predicted	Ratio	Increase
2012	16.1	20.0	1.2	0.7	8.2	8.7	0.95	-0.5
2013	12.4	22.7	3.2	1.1	10.7	10.5	1.02	0.2
2014	16.3	25.6	2.5	1.8	9.8	10.9	0.90	-1.1
2015	11.4	19.9	1.7	1.3	7.2	8.4	0.86	-1.2
2016	20.4	30.8	2.9	3.0	12.3	12.7	0.96	-0.5
2017	37.9	44.5	3.8	6.8	20.6	19.2	1.07	1.4
2018	15.6	20.9	1.2	1.0	8.5	8.8	0.97	-0.2
2019	31.0	37.8	4.9	3.6	16.2	18.1	0.89	-1.9
2020	14.9	24.5	3.1	2.8	10.6	11.3	0.93	-0.8
2021	14.4	22.3	2.5	1.3	9.6	10.1	0.95	-0.5
2022	15.4	20.9	2.9	1.3	11.3	10.8	1.05	0.5
2023	40.1	50.6	5.7	4.6	20.5	21.9	0.94	-1.4
Seeded Mean	21.6	30.2	3.2	2.3	12.6	13.2	**0.95**	**-0.7**

* Seeding conducted in nearby areas but not in target area

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.92059
R Square	0.84749
Adjusted R Square	0.78649
Standard Error	1.23083
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	84.18464	21.046	13.8924	0.0004
Residual	10	15.14942	1.5149		
Total	14	99.33406			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2.50414	1.804771	1.3875	0.19543	-1.5171	6.5254	-1.517	6.525418
X Variable 1	0.22402	0.122163	1.8338	0.09658	-0.0482	0.4962	-0.048	0.496214
X Variable 2	0.05192	0.101297	0.5126	0.61938	-0.1738	0.2776	-0.174	0.277624
X Variable 3	1.21646	0.702718	1.7311	0.11412	-0.3493	2.7822	-0.349	2.782211
X Variable 4	0.186	0.78296	0.2376	0.81702	-1.5585	1.9305	-1.559	1.930547

April 1 Snowpack, Linear Regression Based on 13 Historical Seasons

Regression (non-seeded) period:

Water Year	Control avg	Target avg
1975	29.6	9.9
1976	24.8	10.0
1977	10.2	3.6
1978	29.9	10.5
1979	28.6	14.6
1980	35.3	18.4
1981	16.2	9.5
1982	34.9	14.0
1983	31.9	17.0
1984	27.8	12.2
1985	25.0	11.4
1986	35.1	14.3
1987	14.5	10.4
Mean	26.4	12.0

Seeded period:

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
1989*	24.5	9.0	11.2	0.80	-2.3
1990*	18.6	10.6	9.0	1.18	1.6
1991*	19.9	10.1	9.5	1.06	0.6
1992*	13.8	8.4	7.2	1.16	1.2
1993*	29.2	14.6	13.0	1.12	1.6
1995*	28.7	15.2	12.8	1.19	2.4
2001*	16.6	10.2	8.3	1.23	1.9
2002*	21.2	6.8	10.0	0.68	-3.2
2003	17.0	9.4	8.4	1.11	1.0
2004**	24.6	7.9	11.3	0.70	-3.4
2005	37.0	20.5	15.9	1.29	4.6
2006	35.4	11.0	15.4	0.72	-4.3
2007**	16.7	6.5	8.3	0.79	-1.8
2008	27.4	11.9	12.3	0.97	-0.4
2009	28.5	7.7	12.7	0.60	-5.0
2010	17.2	9.4	8.5	1.11	0.9
2011	41.6	14.1	17.7	0.80	-3.6
2012**	16.1	5.9	8.1	0.73	-2.2
2013	17.4	7.0	8.6	0.81	-1.6
2015**	12.6	2.3	6.8	0.34	-4.4
2016	21.7	10.1	10.2	0.99	-0.1

2017	32.0	14.8	14.1	1.05	0.7
2018	14.2	6.9	7.4	0.93	-0.5
2019	30.8	14.3	13.6	1.05	0.6
2020	24.1	12.7	11.1	1.15	1.6
2021	17.8	8.6	8.7	0.99	-0.1
2022	15.2	9.9	7.7	1.28	2.1
2023	45.7	19.9	19.2	1.03	0.6
Seeded Mean	26.2	11.5	11.9	**0.97**	**-0.4**

* Seeding conducted in nearby areas but not in target area

** Not included in average due to very early and abnormal snow melt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.807491
R Square	0.652042
Adjusted R Square	0.62041
Standard Error	2.344172
Observations	13

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	2.028078	2.285175	0.887493	0.393805	-3.0015
X Variable 1	0.376232	0.082868	4.540157	0.000844	0.19384

April 1 Snowpack, Multiple Linear Regression Based on 13 Historical Seasons

Regression (non-seeded) period:

Water Year	**Timp Div**	**Farm Cyn**	**Lookout**	**Kelley RS**	**Target Avg**
1975	31.6	40.6	25.8	20.5	9.9
1976	26.5	34.2	19.0	19.3	10.0
1977	7.9	17.6	8.8	6.5	3.6
1978	32.3	38.8	24.1	24.4	10.5
1979	33.2	38.7	24.8	17.7	14.6
1980	40.5	43.4	35.1	22.2	18.4
1981	18.3	24.0	13.5	8.9	9.5
1982	39.2	44.1	32.8	23.4	14.0
1983	36.6	43.5	29.9	17.6	17.0
1984	27.0	38.3	26.8	19.0	12.2
1985	25.1	34.3	26.7	13.9	11.4

1986	39.6	43.0	30.2	27.6	14.3
1987	11.6	20.1	16.9	9.3	10.4
Mean	**28.4**	**35.4**	**24.2**	**17.7**	**12.0**

Seeded period:

Water Year	Timp Div	Farm Cyn	Lookout	Kelley RS	Target Avg	Predicted	Ratio	Increase
1989*	19.3	36.5	25.3	16.8	9.0	7.4	1.21	1.5
1990*	21.7	23.7	16.4	12.4	10.6	11.5	0.93	-0.8
1991*	18.3	28.6	20.4	12.4	10.1	9.4	1.08	0.7
1992*	10.1	21.1	12.9	11.0	8.4	5.3	1.58	3.1
1993*	37.1	35.1	27.0	17.7	14.6	17.9	0.82	-3.2
1995*	28.0	39.2	31.5	15.9	15.2	13.8	1.10	1.4
2001*	8.2	27.5	20.3	10.5	10.2	5.0	2.05	5.2
2002*	13.9	34.0	24.1	12.7	6.8	6.4	1.07	0.5
2003	10.7	23.2	20.3	13.8	9.4	6.8	1.39	2.6
2004**	16.7	40.9	28.2	12.7	7.9	6.9	1.14	1.0
2005	40.6	53.1	36.6	17.5	20.5	16.9	1.21	3.6
2006	26.3	53.2	41.7	20.5	11.0	10.2	1.08	0.8
2007**	10.3	24.0	19.4	13.0	6.5	6.2	1.05	0.3
2008	26.7	37.7	29.5	15.6	11.9	13.0	0.92	-1.1
2009	23.6	43.8	30.3	16.3	7.7	9.2	0.84	-1.5
2010	17.8	22.9	18.2	9.8	9.4	11.2	0.84	-1.8
2011	43.7	56.4	44.6	21.5	14.1	19.1	0.73	-5.1
2012**	12.9	20.8	17.8	12.7	5.9	8.2	0.71	-2.4
2014	12.7	31.7	28.2	19.1	7.5	6.0	1.25	1.5
2015**	4.8	20.0	14.1	11.5	2.3	3.2	0.74	-0.8
2016	16.5	30.4	25.4	14.2	10.1	9.1	1.11	1.0
2017	29.2	39.8	33.9	25.0	14.8	12.1	1.22	2.7
2018	8.8	19.6	15.2	13.2	6.9	5.3	1.29	1.6
2019	32.5	41.0	35.0	14.8	14.3	17.3	0.82	-3.0
2020	17.9	31.7	31.1	15.8	12.7	11.0	1.15	1.7
2021	12.7	22.5	23.8	12.0	8.6	10.1	0.86	-1.5
2022	12.7	21.1	17.2	9.8	9.9	8.8	1.13	1.1
2023	48.4	64.1	49.7	20.5	19.9	21.1	0.94	-1.3
Seeded Mean	23.0	36.6	29.4	15.9	11.5	11.2	**1.02**	**0.3**

* Seeding conducted in nearby areas but not in target area
** Not included in average due to very early and abnormal snow melt
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.93716
R Square	0.878269
Adjusted R Square	0.817404

Standard Error	1.625839
Observations	13

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	6.339979	3.026456	2.094853	0.069492	-0.63905	13.319	-0.63905	13.319
Timp Div	0.536956	0.221169	2.427815	0.041343	0.02694	1.046972	0.02694	1.046972
Farm Cyn	-0.36777	0.264512	-1.39037	0.201875	-0.97774	0.242197	-0.97774	0.242197
Lookout	0.388727	0.169898	2.288	0.051425	-0.00306	0.780512	-0.00306	0.780512
Kelley RS	-0.33837	0.174272	-1.9416	0.088128	-0.74024	0.063505	-0.74024	0.063505

April 1 Snowpack, Linear Regression Based on 46 Historical Seasons

Regression (non-seeded) period:

Water Year	Control Avg	Target Avg
1957	25.85	7.97
1958	32.65	10.80
1959	18.20	7.90
1960	22.35	5.87
1961	16.30	5.20
1962	32.75	16.23
1963	17.80	5.67
1964	20.40	5.27
1965	32.60	9.73
1966	21.75	9.10
1967	27.10	10.23
1968	27.70	10.60
1969	40.05	16.80
1970	24.15	8.07

1971	28.10	9.53
1972	28.25	7.60
1973	31.35	10.90
1974	24.40	5.03
1975	36.10	9.07
1976	30.35	8.93
1977	12.75	2.47
1978	35.55	9.87
1979	35.95	13.03
1980	41.95	17.67
1981	21.15	8.03
1982	41.65	12.50
1983	40.05	16.40
1984	32.65	11.50
1985	29.70	10.40
1986	41.30	12.53
1987	15.85	7.40
1988	13.40	5.27
1989	27.90	7.27
1990	22.70	8.60
1991	23.45	9.37
1992	15.60	7.07
1993	36.10	14.07
1994	21.90	7.70
1996	28.05	8.03
1997	43.90	13.50
1998	33.35	10.10
1999	21.35	6.00
2000	28.60	10.33
2001	17.85	8.63
2002	23.95	5.93
Mean	**27.8**	**9.5**

Seeded period:

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
2003	16.95	8.93	5.78	1.55	3.2
2004**	28.80	6.30	9.86	0.64	-3.6
2005	46.85	19.63	16.09	1.22	3.5
2006	39.75	10.33	13.64	0.76	-3.3
2007**	17.15	3.93	5.84	0.67	-1.9
2008	32.20	11.70	11.04	1.06	0.7
2009	33.70	6.67	11.55	0.58	-4.9
2010	20.35	8.07	6.95	1.16	1.1
2011	50.05	13.57	17.19	0.79	-3.6
2012**	16.85	3.87	5.74	0.67	-1.9
2013	20.20	6.10	6.90	0.88	-0.8
2014	22.20	6.47	7.59	0.85	-1.1

2015**	12.40	1.50	4.21	0.36	-2.7
2016	23.45	8.60	8.02	1.07	0.6
2017	34.50	13.77	11.83	1.16	1.9
2018	14.20	4.83	4.83	1.00	0.0
2019	36.75	13.57	12.60	1.08	1.0
2020	24.80	11.07	8.48	1.30	2.6
2021	17.60	7.13	6.00	1.19	1.1
2022	16.90	9.10	5.76	1.58	3.3
2023	56.25	20.70	19.33	1.07	1.4
Seeded Mean	29.8	10.6	10.2	**1.04**	**0.4**

** Not included in average due to very early snow melt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.836371208
R Square	0.699516797
Adjusted R Square	0.692687634
Standard Error	1.885329949
Observations	46

	Coefficients	*Standard Error*
Intercept	-0.07114187	0.987139943
X Variable 1	0.344927472	0.034081011

April 1 Snowpack, Multiple Linear Regression Based on 46 Historical Seasons

Water Year	**Farmington Cyn**	**Timpanogos**	**Target Avg**
1957	26.40	25.30	7.97
1958	33.90	31.40	10.80
1959	21.10	15.30	7.90
1960	25.40	19.30	5.87
1961	21.80	10.80	5.20
1962	35.40	30.10	16.23
1963	20.50	15.10	5.67
1964	23.90	16.90	5.27
1965	38.60	26.60	9.73
1966	22.10	21.40	9.10

1967	23.00	31.20	10.23
1968	30.50	24.90	10.60
1969	36.40	43.70	16.80
1970	30.30	18.00	8.07
1971	38.70	17.50	9.53
1972	37.60	18.90	7.60
1973	33.70	29.00	10.90
1974	30.90	17.90	5.03
1975	40.60	31.60	9.07
1976	34.20	26.50	8.93
1977	17.60	7.90	2.47
1978	38.80	32.30	9.87
1979	38.70	33.20	13.03
1980	43.40	40.50	17.67
1981	24.00	18.30	8.03
1982	44.10	39.20	12.50
1983	43.50	36.60	16.40
1984	38.30	27.00	11.50
1985	34.30	25.10	10.40
1986	43.00	39.60	12.53
1987	20.10	11.60	7.40
1988	16.10	10.70	5.27
1989	36.50	19.30	7.27
1990	23.70	21.70	8.60
1991	28.60	18.30	9.37
1992	21.10	10.10	7.07
1993	35.10	37.10	14.07
1994	25.70	18.10	7.70
1995	39.20	28.00	13.53
1997	51.60	36.20	13.50
1998	43.50	23.20	10.10
1999	27.50	15.20	6.00
2000	39.20	18.00	10.33
2001	27.50	8.20	8.63
2002	34.00	13.90	5.93
Mean	**32.0**	**23.5**	**9.5**

Water Year	Farmington Cyn	Timpanogos	Target avg	Predicted	Ratio	Increase
2003	23.20	10.70	8.93	5.51	1.62	3.4
2004**	40.90	16.70	6.30	8.28	0.76	-2.0
2005	53.10	40.60	19.63	15.45	1.27	4.2
2006	53.20	26.30	10.33	11.65	0.89	-1.3
2007**	24.00	10.30	3.93	5.46	0.72	-1.5
2008	37.70	26.70	11.70	10.73	1.09	1.0
2009	43.80	23.60	6.67	10.31	0.65	-3.6
2010	22.90	17.80	8.07	7.38	1.09	0.7

2011	56.40	43.70	13.57	16.49	0.82	-2.9
2012**	20.80	12.90	3.87	5.94	0.65	-2.1
2013	30.70	9.70	6.10	5.74	1.06	0.4
2014	31.70	12.70	6.47	6.61	0.98	-0.1
2015**	20.00	4.80	1.50	3.73	0.40	-2.2
2016	30.40	16.50	8.60	7.53	1.14	1.1
2017	39.80	29.20	13.77	11.53	1.19	2.2
2018	19.60	8.80	4.83	4.77	1.01	0.1
2019	41.00	32.50	13.57	12.49	1.09	1.1
2020	31.70	17.90	11.07	7.99	1.38	3.1
2021	22.50	12.70	7.13	6.00	1.19	1.1
2022	21.10	12.70	9.10	5.91	1.54	3.2
2023	64.10	48.40	20.70	18.25	1.13	2.4
Seeded Mean	36.6	23.0	10.6	9.7	**1.10**	**0.9**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.859094313
R Square	0.738043039
Adjusted R Square	0.719331828
Standard Error	1.801747514
Observations	46

	Coefficients	*Standard Error*
Intercept	1.132749671	1.060535368
Farmington Cyn	0.066018713	0.045897051
Timpanogos	0.266315504	0.046335651

March – July Streamflow Linear Regression, with 5 Control and 3 Target Sites; units are in acre feet

Regression (non-seeded) Period:

Water Year	**Control avg**	**Target Avg**
1966	112936	49949
1971	261215	66992
1972	178150	59875
1973	193597	72462
1974	212877	43409
1975	197588	79701

1976	169736	48415
1977	44359	25649
1978	227917	53303
1979	191656	45339
1983	279948	96463
1984	331384	69498
1985	222233	57727
1986	276152	96943
1987	116536	64515
1988	139135	36566
1989	105895	32889
1990	89112	51965
1991	120377	54937
1992	81594	38662
1993	212713	78967
1994	83576	38992
1995	245111	105683
1996	189341	52819
1997	263786	76363
1998	215275	81533
1999	215124	75497
2000	120952	40342
2001	113842	62042
2002	58672	19379
Mean	**175693**	**59229**

Seeded Period:

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
2003	123438	47931	47895	1.00	36
2004	90888	40375	40836	0.99	-460
2005	174888	101668	59055	1.72	42614
2006	152841	54263	54273	1.00	-10
2007	105346	33724	43971	0.77	-10248
2008	207348	45549	66095	0.69	-20546
2009	219964	54665	68831	0.79	-14166
2010	175017	51930	59082	0.88	-7152
2011	365025	103727	100293	1.03	3433
2012	79824	29931	38436	0.78	-8505
2013	80584	36523	38601	0.95	-2077
2014	177875	35639	59702	0.60	-24063
2015	149671	51525	53585	0.96	-2060
2016	178270	61738	59788	1.03	1950
2017	189133	83172	62144	1.34	21028

2018	94881	30575	41702	0.73	-11127
2019	192441	85429	62861	1.36	22567
2020	128875	51130	49075	1.04	2056
2021	60566	25790	34259	0.75	-8469
2022	106325	39712	44184	0.90	-4472
Seeded Mean	152660	53250	54233	**0.98**	**-984**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.749069335
R Square	0.561104868
Adjusted R Square	0.545430042
Standard Error	14338.66364
Observations	30

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	21123.14391	6886.056	3.06752417	0.00475	7017.681
X Variable 1	0.216890053	0.036251	5.98302272	1.92E-06	0.142633

High Uintas March – July Streamflow Multiple Linear Regression, with 5 Control and 3 Target Sites; units are in acre feet

Regression (non-seeded) Period:

Water Year	**Hams Fk**	**Fontenelle**	**Smiths Fk**	**Little Snake**	**White River**	**Target Avg**
1966	44794	26481	69071	261819	162515	49949
1971	145432	70383	178721	590894	320645	66992
1972	103820	75862	158637	301634	250798	59875
1973	48082	29485	75594	476355	338467	72462
1974	80404	46964	127332	498440	311243	43409
1975	81706	45447	115301	396510	348975	79701
1976	75548	52151	120425	329104	271451	48415
1977	7077	7711	23732	85711	97566	25649
1978	93460	58383	142896	471055	373789	53303
1979	53667	33706	80654	396038	394214	45339
1983	102494	73684	153030	617221	453311	96463
1984	103004	56974	147686	809511	539744	69498
1985	49380	32445	86070	470868	472404	57727

1986	128700	95836	186880	499949	469394	96943
1987	36867	24696	51531	219782	249806	64515
1988	36184	24103	64874	298988	271525	36566
1989	46081	30952	84247	170223	197970	32889
1990	33395	23630	62426	171219	154892	51965
1991	44451	23899	77260	213547	242727	54937
1992	23469	10950	48549	140134	184870	38662
1993	69422	33656	122948	457750	379790	78967
1994	27123	17019	46243	176877	150618	38992
1995	57851	40953	106167	564912	455670	105683
1996	72113	40088	129123	364185	341195	52819
1997	91551	59499	165808	589422	412650	76363
1998	58520	41232	102936	458203	415485	81533
1999	80859	69012	137185	480812	307753	75497
2000	37484	23018	70236	244056	229966	40342
2001	20646	14235	44049	238488	251794	62042
2002	24183	18504	49405	93630	107637	19379
Seeded Mean	62592	40032	100967	369578	305295	59229

Seeded Period:

Water Year	Hams Fork	Fontenelle	Smiths Fork	Little Snake	White River	Target Avg	Predicted	Ratio	Increase
2003	26134	29925	57863	242638	260630	47931	57296	0.84	-9365
2004	30335	23304	60098	152754	187948	40375	43108	0.94	-2733
2005	57851	53163	113152	322611	309446	101668	66848	1.52	34820
2006	72113	43893	95628	235021	332619	54263	59780	0.91	-5516
2007	91551	19643	52585	215647	209043	33724	32320	1.04	1404
2008	58520	33729	81623	512575	353108	45549	65572	0.69	-20023
2009	80859	41152	117741	542915	332130	54665	61026	0.90	-6361
2010	37484	34226	71247	470661	251381	51930	60795	0.85	-8865
2011	20646	82651	159392	943100	534183	103727	124156	0.84	-20430
2012	24183	23792	64335	134015	138679	29931	39259	0.76	-9328
2013	26134	17708	57232	121059	180197	36523	39173	0.93	-2650
2014	81110	53750	107247	324809	322459	35639	64300	0.55	-28661
2015	58245	39208	95950	237787	317166	51525	58174	0.89	-6649
2016	59483	34884	90428	420466	286091	61738	57181	1.08	4557
2017	122630	93600	183955	307629	237851	83172	79093	1.05	4079
2018	46705	32380	90296	142410	162616	30575	37738	0.81	-7163
2019	44728	35265	91752	394096	396364	85429	66959	1.28	18469
2020	40893	31271	83105	292991	196115	51130	44272	1.15	6858

2021	21740	16921	47579	98823	117765	25790	26708	0.97	-918
2022	25289	21692	65550	225356	193737	39712	44758	0.89	-918
Avg	53335	38108	89338	316868	265976	53250	56152	**0.95**	**-2902**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.788019316
R Square	0.620974442
Adjusted R Square	0.542010784
Standard Error	14392.49006
Observations	30

	Coefficients
Intercept	19093.5744
Hams Fork	-0.20489592
Fontenelle	0.648935056
Smiths Fork	-0.09760667
Little Snake	0.022804631
White River	0.093055464

High Uintas March – July Streamflow Linear Regression, with 3 Wyoming Control Sites and 3 Target Sites; units are in acre feet

Regression (non-seeded) Period:

Water Year	Control Avg	Target Avg
1966	46782	49949
1971	131512	66992
1972	112773	59875
1973	51054	72462
1974	84900	43409
1975	80818	79701
1976	82708	48415
1977	12840	25649
1978	98246	53303
1979	56009	45339
1983	109736	96463
1984	102555	69498
1985	55965	57727

1986	137139	96943
1987	37698	64515
1988	41720	36566
1989	53760	32889
1990	39817	51965
1991	48537	54937
1992	27656	38662
1993	75342	78967
1994	30128	38992
1995	68324	105683
1996	80441	52819
1997	105619	76363
1998	67563	81533
1999	95685	75497
2000	43579	40342
2001	26310	62042
2002	30697	19379
Mean	**67864**	**59229**

Seeded Period:

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
2003	37974	47931	47492	1.01	439
2004	37912	40375	47468	0.85	-7093
2005	80795	101668	64307	1.58	37361
2006	65521	54263	58309	0.93	-4046
2007	34013	33724	45937	0.73	-12213
2008	57019	45549	54971	0.83	-9422
2009	74925	54665	62002	0.88	-7337
2010	51014	51930	52613	0.99	-683
2011	115947	103727	78110	1.33	25616
2012	42142	29931	49129	0.61	-19198
2013	33887	36523	45888	0.80	-9364
2014	80702	35639	64271	0.55	-28632
2015	64468	51525	57896	0.89	-6370
2016	61598	61738	56769	1.09	4969
2017	133395	83172	84962	0.98	-1790
2018	56460	30575	54751	0.56	-24177
2019	57248	85429	55061	1.55	30368
2020	51756	51130	52904	0.97	-1774
2021	28747	25790	43869	0.59	-18079
2022	37510	39712	47310	0.84	-7598
Seeded Mean	61343	53962	56669	**0.95**	**-2706**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.609172
R Square	0.371091
Adjusted R Square	0.34863
Standard Error	17164.15
Observations	30

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	32580.86	7266.534	4.48368633	0.000114	17696.02
X Variable 1	0.392674	0.096607	4.06467088	0.000353	0.194784

High Uintas March – July Streamflow Multiple Linear Regression, with 3 Wyoming Control Sites and 3 Target Sites; units are in acre feet

Regression (non-seeded) Period:

Water Year	Hams Fork	Fontenelle	Smiths Fork	Target Avg
1966	44794	26481	69071	49949
1971	145432	70383	178721	66992
1972	103820	75862	158637	59875
1973	48082	29485	75594	72462
1974	80404	46964	127332	43409
1975	81706	45447	115301	79701
1976	75548	52151	120425	48415
1977	7077	7711	23732	25649
1978	93460	58383	142896	53303
1979	53667	33706	80654	45339
1983	102494	73684	153030	96463
1984	103004	56974	147686	69498
1985	49380	32445	86070	57727
1986	128700	95836	186880	96943
1987	36867	24696	51531	64515
1988	36184	24103	64874	36566
1989	46081	30952	84247	32889
1990	33395	23630	62426	51965
1991	44451	23899	77260	54937
1992	23469	10950	48549	38662
1993	69422	33656	122948	78967
1994	27123	17019	46243	38992
1995	57851	40953	106167	105683

1996	72113	40088	129123	52819
1997	91551	59499	165808	76363
1998	58520	41232	102936	81533
1999	80859	69012	137185	75497
2000	37484	23018	70236	40342
2001	20646	14235	44049	62042
2002	24183	18504	49405	19379
Average	**62592**	**40032**	**100967**	**59229**

Seeded Period:

Water Year	Hams Fork	Fontenelle	Smiths Fork	Target Avg	Predicted	Ratio	Increase
2003	26134	29925	57863	47931	52856	0.91	-4924
2004	30335	23304	60098	40375	49158	0.82	-8782
2005	76070	53163	113152	101668	65107	1.56	36561
2006	57043	43893	95628	54263	61159	0.89	-6896
2007	29811	19643	52585	33724	45597	0.74	-11874
2008	55706	33729	81623	45549	53019	0.86	-7470
2009	65884	41152	117741	54665	63245	0.86	-8580
2010	47569	34226	71247	51930	52717	0.99	-787
2011	105799	82651	159392	103727	83343	1.24	20384
2012	38298	23792	64335	29931	48385	0.62	-18453
2013	26722	17708	57232	36523	46693	0.78	-10170
2014	81110	53750	107247	35639	62524	0.57	-26885
2015	58245	39208	95950	51525	58683	0.88	-7158
2016	59483	34884	90428	61738	54856	1.13	6882
2017	122630	93600	183955	83172	90500	0.92	-7327
2018	46705	32380	90296	30575	57002	0.54	-26427
2019	44728	35265	91752	85429	59282	1.44	26147
2020	40893	31271	83105	51130	56143	0.91	-5013
2021	21740	16921	47579	25790	45130	0.57	-19340
2022	25289	21692	65550	39712	51134	0.78	-11422
Seeded Mean	53010	38108	89338	53250	57826	**0.92**	**-4577**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.629376912
R Square	0.396115297
Adjusted R Square	0.326436293
Standard Error	17454.10769
Observations	30

	Coefficients	*Standard Error*
Intercept	30446.25283	9346.848154
Hams Fork	-0.26435458	0.430607215
Fontenelle	0.478306208	0.486930199
Smiths Fork	0.259311656	0.340472822

APPENDIX E: GLOSSARY OF RELEVANT METEOROLOGICAL TERMS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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