Cloud Seeding Annual Report

Western Uintas Program
2019-2020 Winter Season

Prepared For:

State of Utah, Division of Water Resources

Weber Basin Water Conservancy District

Provo River Water Users Association

Central Utah Water Conservancy District

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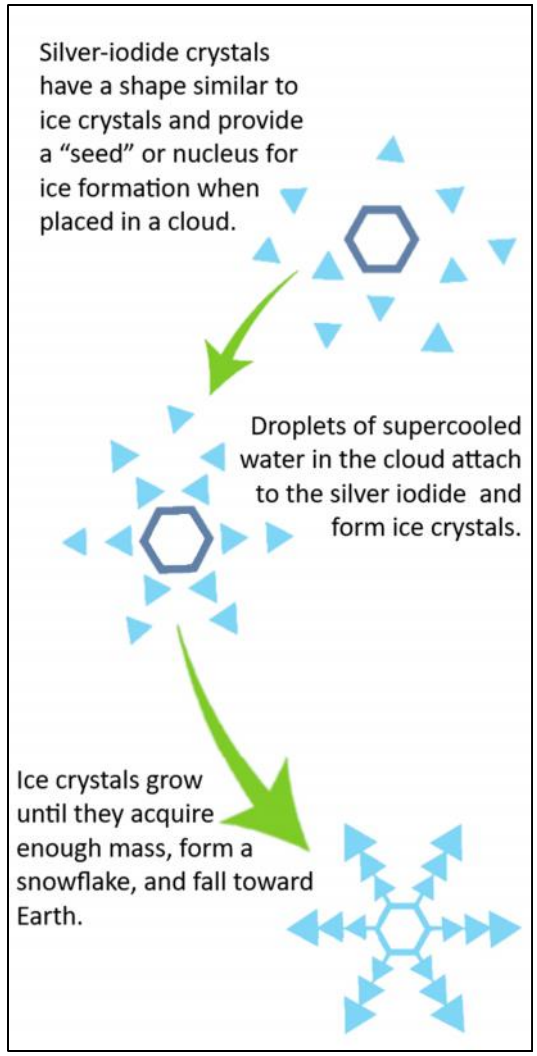
WEATHER MODIFICATION

The Science Behind Cloud Seeding

The Science

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

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

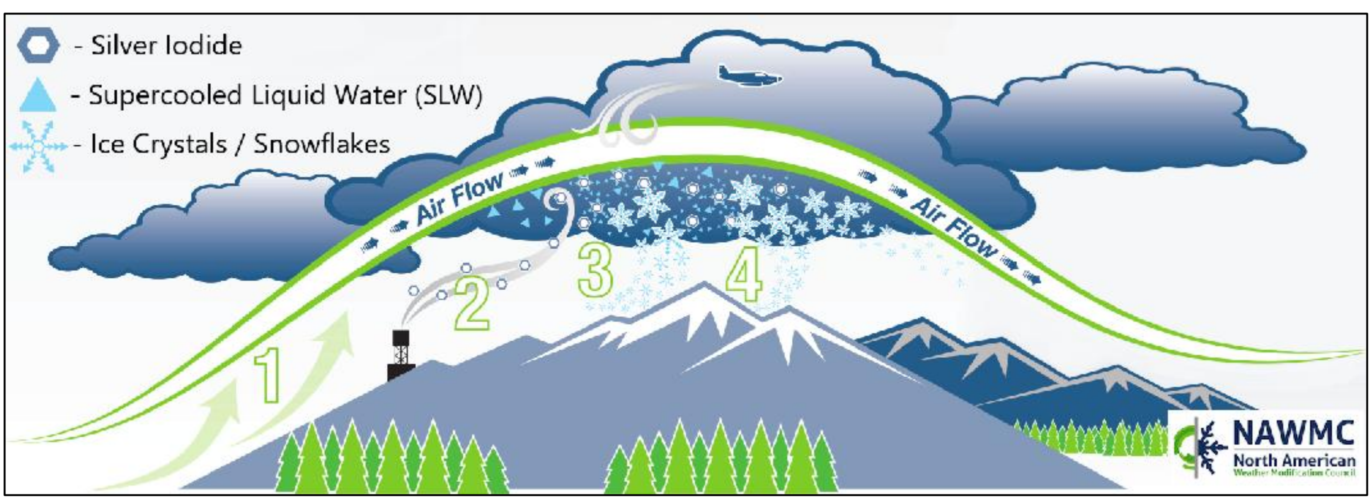


Safety

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

Effectiveness

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



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EXECUTIVE SUMMARY

A total of 25 winter seasons of cloud seeding have been conducted in portions of the western Uinta Range in Utah. The Western Uintas program utilizes 12 ground-based, manually-operated (Cloud Nuclei Generator, or CNG) sites, containing a 2% silver iodide solution. The goal of the seeding program is to augment wintertime snowpack/precipitation over the seeded watersheds. The areas targeted for seeding have included the upper portions of both the Weber River and the Provo River drainages in most years.

Precipitation and snowfall were generally near normal during the 2019-2020 winter season, with snow water equivalent for the Weber-Ogden River basin averaging about 99% of the median value on April 1st. The water year precipitation through April 1st averaged 91% of the normal (mean value) across the basin. The Provo River basin had corresponding April 1st averages of 104% of median snowpack and 88% of mean precipitation. A total of 956.75 CNG hours were conducted during 18 storm periods this season, out of a maximum budgeted 2,500 hours. There were no seeding suspensions during the 2019-2020 season.

Evaluations of the effectiveness of the cloud seeding program were made for both the past winter season and for the 25 seeded winter seasons combined. These evaluations utilize SNOTEL records collected by the Natural Resources Conservation Service (NRCS) at selected sites within and surrounding the seeded target area. Analyses of the effects of seeding on target area precipitation and snow water content have been conducted for this seeding program, utilizing target/control comparison techniques.

Based on available historical data, December through March precipitation evaluations have only 11 historical years (prior to seeding operations) available for analysis. Because of this, the focus of the target/control evaluation for this particular seeding program is on the April 1st snow water content analyses which has 23 seasons of available historical data, utilizing manual snow course data that was collecting at most of these same sites prior to the beginning of the SNOTEL network. Both linear and multiple linear regression equations were developed, and (using snow water equivalent) have suggested 4% to 6% increases in April 1st snow water content that can reasonably be attributed to the cloud seeding program. If an 5% snowpack increase due to seeding is assumed, a corresponding average seasonal increase of approximately 0.8" of water across the target area would yield approximately 25,000 additional acre-feet of runoff annually. Sections 5.0 and 6.0 of the report contain further discussion of these mathematical analyses, and estimates of the likely value and cost/benefit ratio of the seeding program.

CLOUD SEEDING ANNUAL REPORT, WESTERN UINTAS PROGRAM
2019-2020 SEASON

1.0 INTRODUCTION

Due to high natural precipitation variability and the increasing demand for water, cloud seeding has been conducted in some parts of Utah for over 40 years, helping to augment water supplies. Cloud seeding in Utah is regulated by the Utah Department of Natural Resources through the Division of Water Resources. After complying with various permit requirements, NAWC was granted a license and permit to conduct cloud seeding for the Western Uintas program watersheds. A cloud seeding program was conducted again during the 2019-2020 winter season for the Upper Weber and Provo River Basins. Cloud seeding programs have been conducted in this area by North American Weather Consultants dating back to 1989. These programs have often been jointly sponsored by two agencies: the Provo River Water Users Association and the Weber Basin Water Conservancy District.

The Weber Basin Water Conservancy District's participation has been continuous since the project's inception while the Provo River Water Users Association opted out during water years 2006 to 2012. The Provo River Water Users Association rejoined the program for the 2012-13 season through the present. Twelve ground-based silver iodide cloud-nucleating generators (CNG's) were installed for this past winter season's program. The program this season became operational on December 1, 2019 and ended on March 31, 2020.

This report provides information about the operational cloud seeding and results of statistical analyses toward estimations of cloud seeding effects. 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 discusses the types of real-time and forecast meteorological data that are used for conduct of the seeding programs. Section 4.0 summarizes the seeding operations conducted during this past season. Section 5.0 details statistical evaluations of the effects of the cloud seeding program. A summary and recommendations for future seasons are given in Section 6.0.

2.0 PROJECT DESIGN

2.1 Background

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

2.2 Seeding Criteria

Project operations have utilized a selective seeding approach, which has proven to be the most efficient and cost-effective method, and has provided the most beneficial results. Selective seeding, or seeding only of storms or portions of storms in which precipitation has a reasonable chance of being enhanced, is based on several criteria which determine the seedability of the winter storms. These criteria deal with key characteristics of the air mass (temperature, stability, wind flow and moisture content), both in and below the precipitating clouds. Table 2-1 provides a summary of the criteria.

2.3 Equipment and Project Set Up

In the fall of 2019 NAWC reinstalled ground-based cloud seeding generators for the winter seeding program. The generators were placed at carefully selected sites, to provide seeding plumes that would be effective in enhancing snowfall over the project target area. Climatological winter storm behavior and prevailing wind direction are major factors in the placement of these sites. Twelve seeding sites were installed for this year's seeding program, whose locations are shown in Figure 2.1. Occasionally, seeding sites installed for other seeding programs in the region (such as Northern Utah and High Uintas programs) are used to target the Western Uintas program during less commonly occurring wind flow situations.

Table 2-1
NAWC Winter Cloud Seeding Criteria

1)	CLOUD BASES ARE BELOW THE MOUNTAIN BARRIER CREST.
2)	LOW-LEVEL WIND DIRECTIONS AND SPEEDS THAT WOULD FAVOR THE MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THEIR RELEASE POINTS INTO THE INTENDED TARGET AREA.
3)	NO LOW-LEVEL ATMOSPHERIC INVERSIONS OR STABLE LAYERS THAT WOULD RESTRICT THE VERTICAL MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THE SURFACE TO AT LEAST THE -5°C (23°F) LEVEL OR COLDER.
4)	TEMPERATURE AT MOUNTAIN BARRIER CREST HEIGHT EXPECTED TO BE -5°C (23°F) OR COLDER.
5)	TEMPERATURE AT THE 700 MB LEVEL (APPROXIMATELY 10,000 FEET) EXPECTED TO BE WARMER THAN -15°C (5°F).

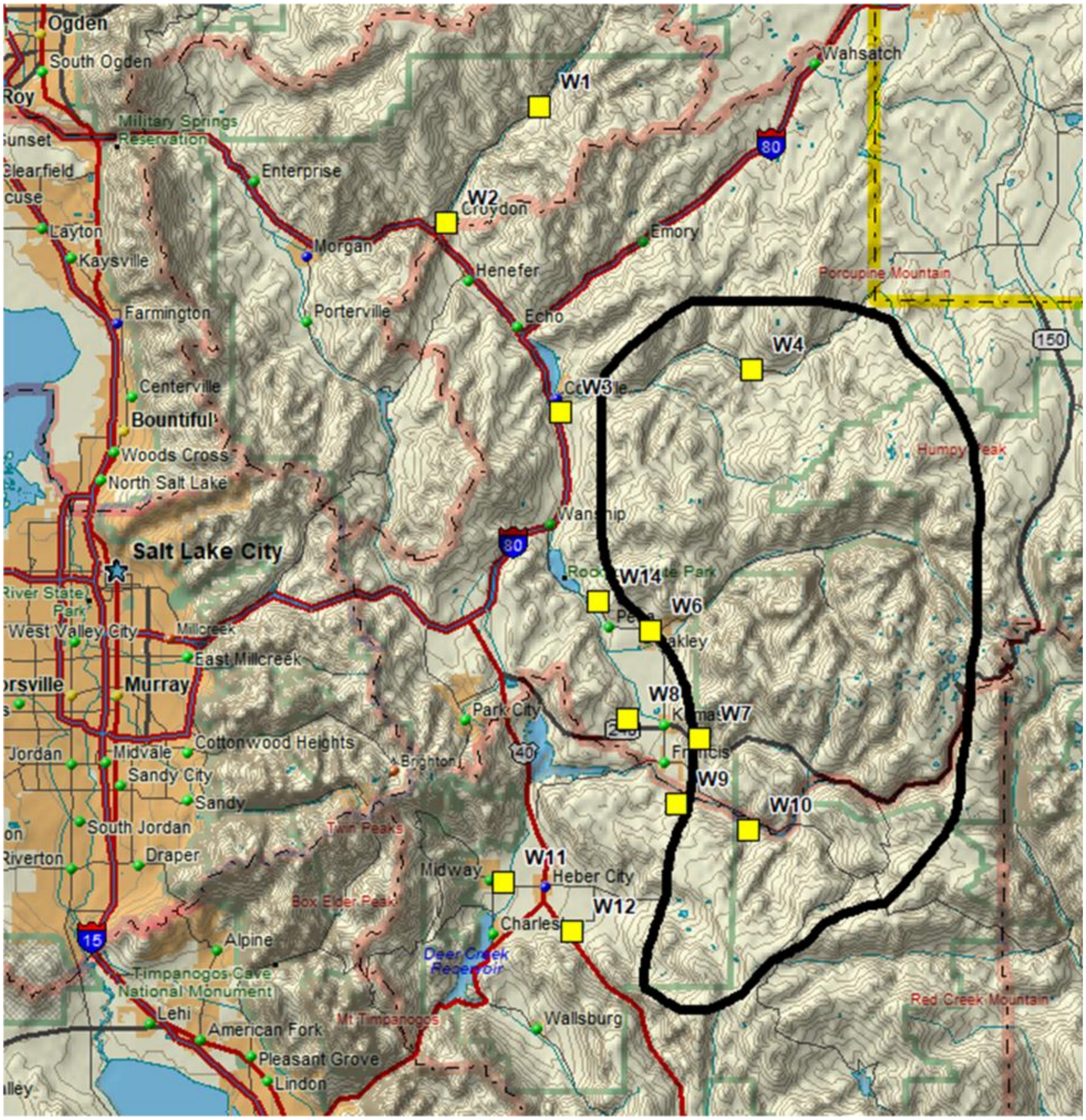


Figure 2.1 Western Uintas target area and ground-based cloud seeding generator locations.

2.3.1 Ground-Based Manual Generators

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

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

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

Figure 2.2 Manually operated cloud seeding generator

Cloud seeding generators were sited at 12 locations (mostly in the valleys), ranging from the southwest to northwest sides of the target area, as shown in Figure 2.1. Pertinent CNG site information is provided in Table 2-2. Most of the winter storms that affect the northern Utah Mountains are associated with synoptic weather systems that move into Utah from the northwest, west or southwest. Usually they consist of a frontal system and/or an upper trough with the winds preceding the front or trough blowing from the south or southwest. As each system passes through the area, the wind flow changes to the west, northwest, or north. Clouds and precipitation may precede as well as follow the front/trough passage, or they may occur primarily after the passage along the boundary of the colder air mass that moves into the region. For the region comprising the project target area, the most abundant precipitation and low-mid level moisture usually occurs in west to northwest flow patterns. This is when the best seeding opportunities typically occur. Southwesterly flow is generally associated with somewhat warmer conditions that are sometimes less seedable.

Table 2-2

Cloud Seeding Generator Sites

Site ID	Site Name	Elev.(Ft)	Lat (N)	Long (W)
1	Lost Creek Reservoir	5525	41° 07.10'	111° 29.32'
2	Croyden	5371	41° 04.12'	111° 30.83'
3	Coalville	5587	40° 55.95'	111° 20.72'
4	Pineview	6407	40° 56.39'	111° 10.18'
6	Oakley	6472	40° 43.07'	111° 18.00'
7	Kamas	6489	40° 38.43'	111° 16.77'
8	Kamas West	6872	40° 38.16'	111° 19.33'
9	Woodland	6706	40° 34.89'	111° 13.81'
10	Woodland East	7305	40° 33.35'	111° 06.80'
11	Midway	5570	40° 30.59'	111° 28.64'
12	Heber City	5810	40° 29.73'	111° 22.52'
14	Peoa	6148	40° 43.75'	111° 20.61'

2.3.2 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. No suspensions were required for the Western Uintas program during the 2019-2020 operations season.

3.0 WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

NAWC maintains a fully equipped project operations center at its Sandy, Utah headquarters. Meteorological information is acquired online from a wide variety of 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 during the 2019-2020 winter season. Figure 3.4 provides predictions of ground-based seeding plume dispersion for a discrete storm period in central and southern Utah 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 important tools for operational meteorologists. These models forecast a variety of parameters at different levels of the atmosphere, including winds, temperatures, moisture, and surface parameters such as accumulated precipitation. An example of a display from the global GFS forecast model is shown in Figures 3.5.

A more recent meteorological product utilized by NAWC to improve operational efficiency is a customized High-Resolution Rapid Refresh (HRRR) model data display and analysis package, developed by Idaho Power Company. The HRRR contains important atmospheric parameters in much finer time and space resolution than other (e.g. global) weather forecast models. Most importantly, this model identifies the presence of Supercooled Liquid Water, the primary target of Cloud Seeding. NAWC is working closely with the Atmospheric Research Center at Utah State University to aid in the development of a forecast model that will predict or forecast relative concentrations of supercooled liquid water in storms developing over the Uinta Range.

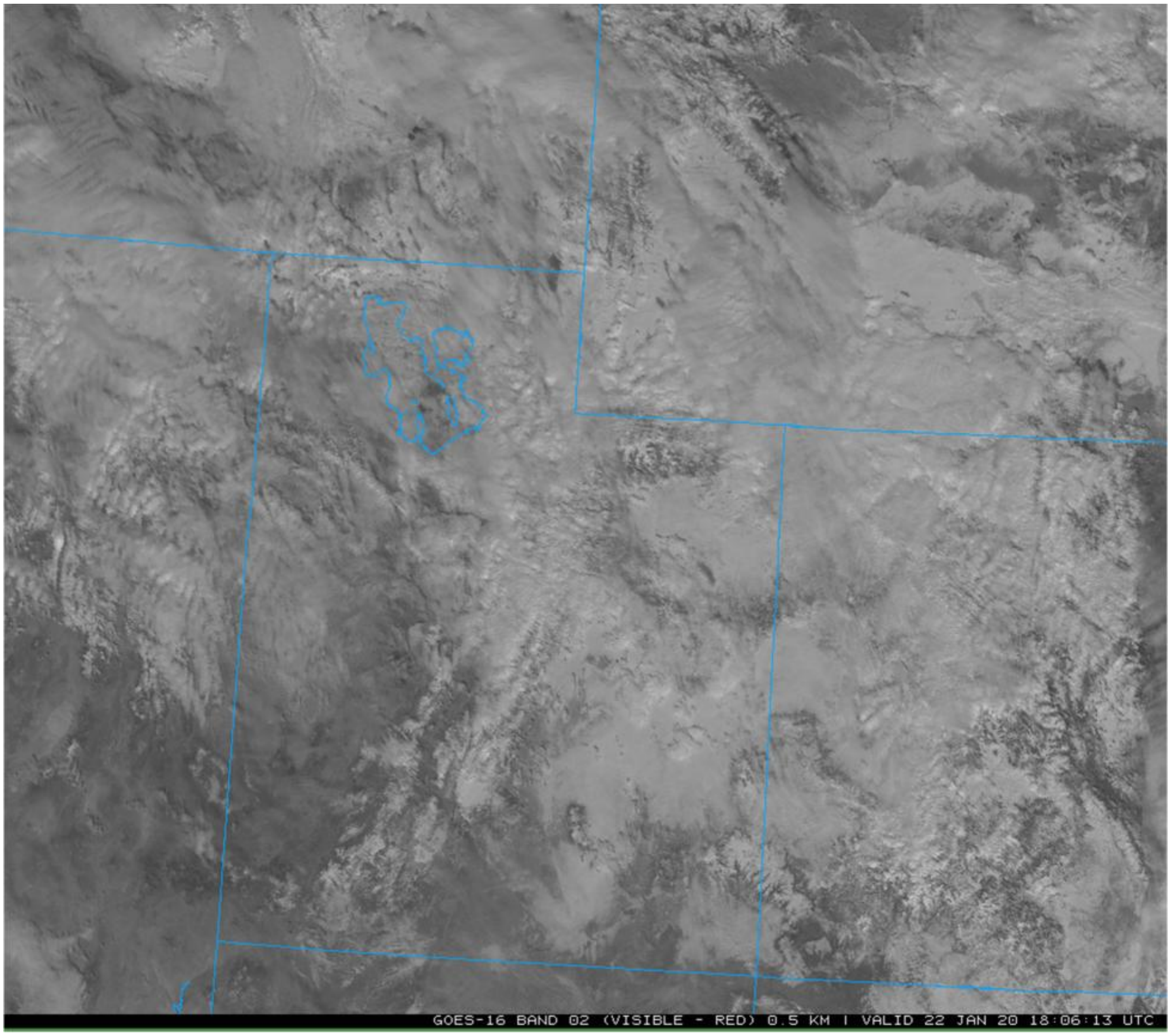


Figure 3.1 Visible spectrum satellite image on January 22, 2020 during a seeded event

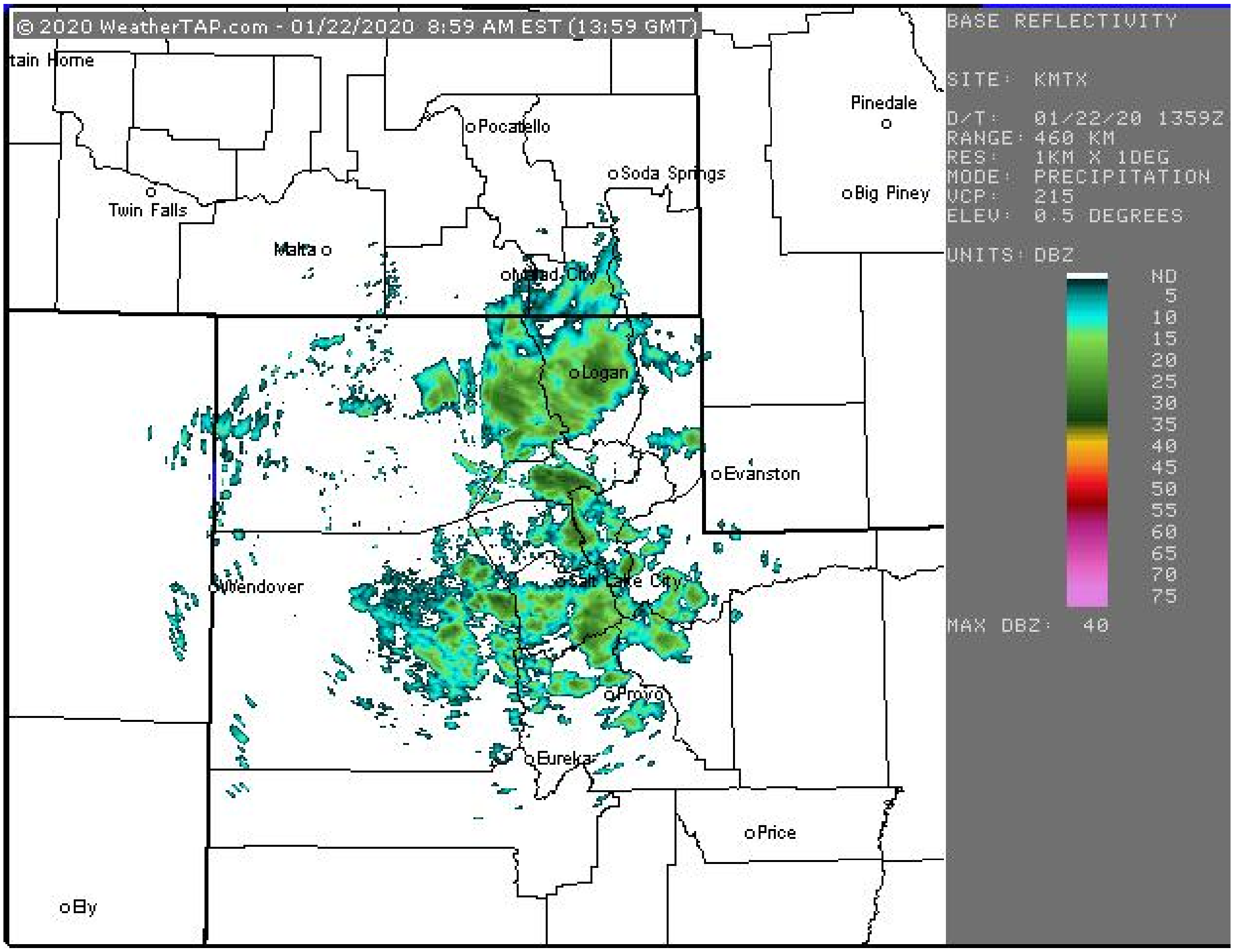


Figure 3.2 Weather radar image over northern Utah, on the morning of January 22, 2020

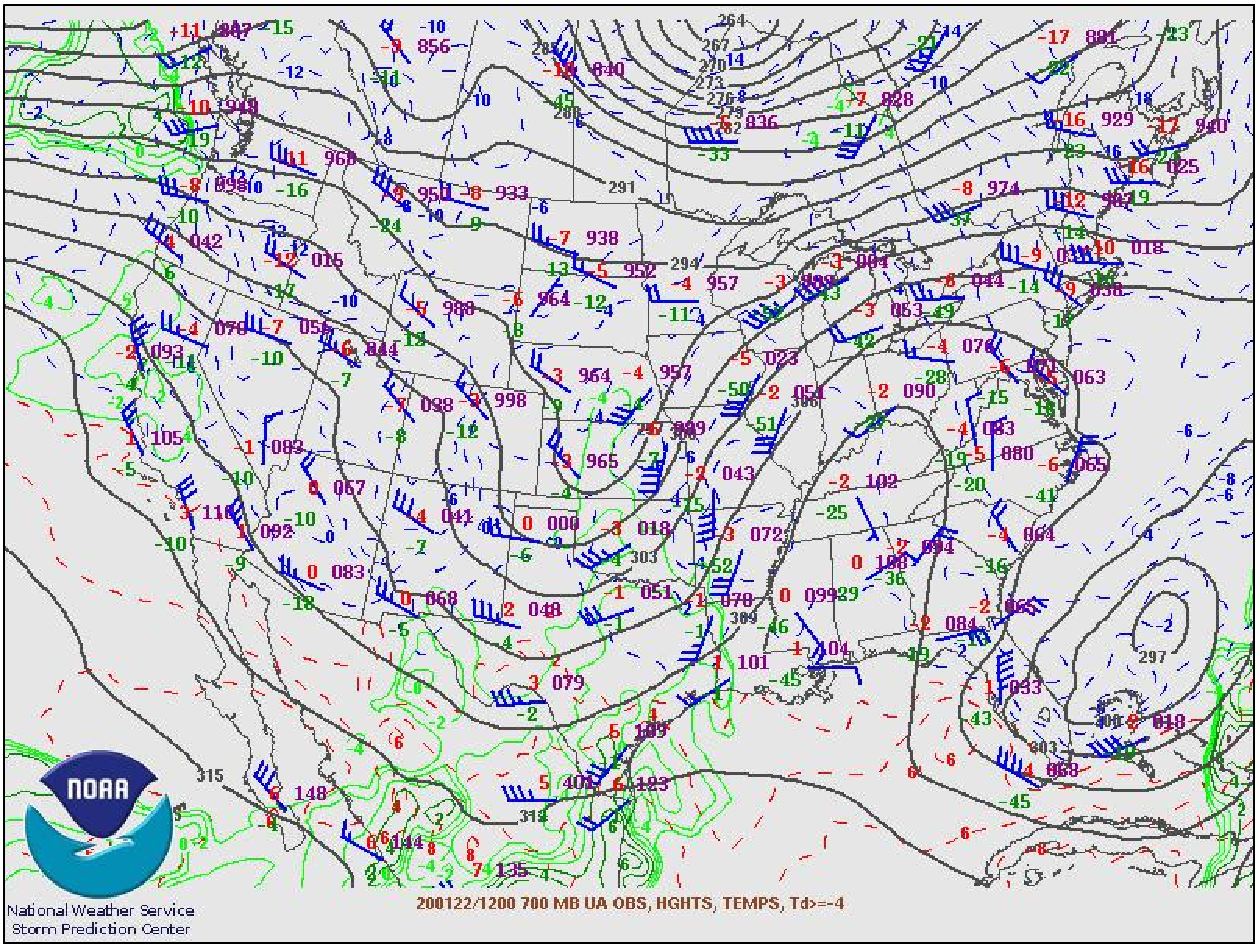


Figure 3.3 U.S. 700 mb map on January 22, illustrating the larger scale weather pattern across the region. This map includes variables such as 700-mb height, winds, temperature and moisture fields.

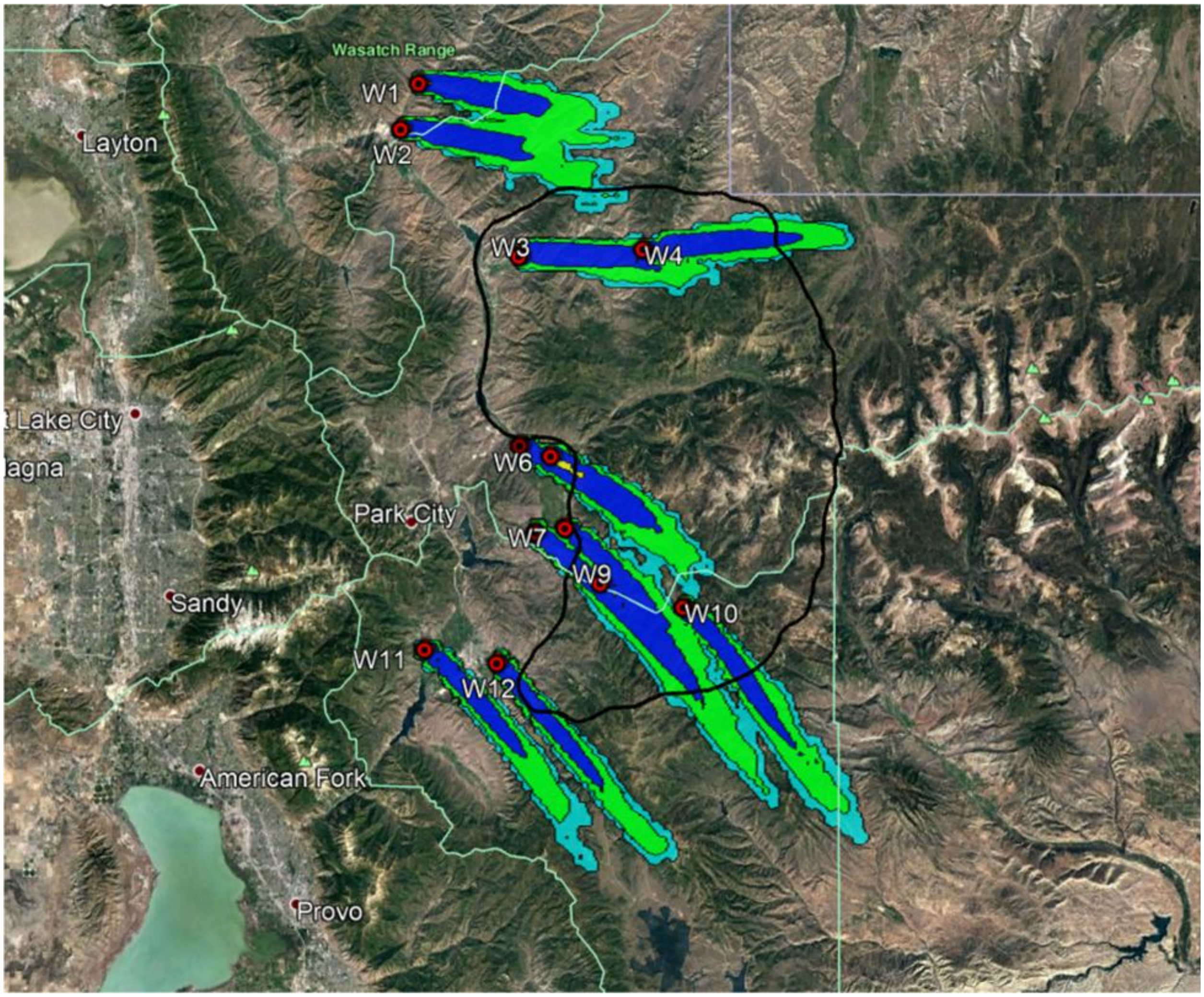
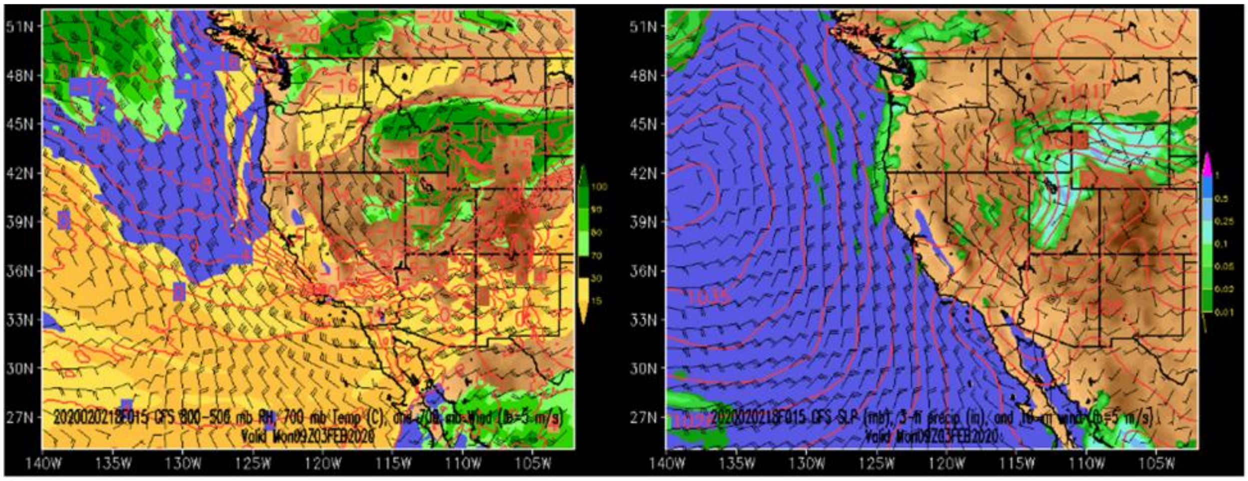


Figure 3.4 HYSPLIT plume dispersion forecast during a storm period early on February 3, from all potential sites. These plots can help the meteorologist to select the appropriate sites to utilize in a given situation.



Figures 3.5 GFS (Global Forecast Systems) model plot during a storm event on the night of February 2-3. These types of plots provide analyses and forecasts for things such as wind, temperatures, moisture at various levels of the atmosphere, as well as surface parameters such as accumulated precipitation.

4.0 OPERATIONS

The 2019-2020 Western Uintas cloud seeding program for the Weber and Provo River basins began on December 1st, 2019 and ended on March 31st, 2020. A total of 18 storm periods were seeded during all or portions of 29 days. Four storms were seeded in December, seven in January, two in February, and five in March. A total of 956.75 seeding generator hours were conducted this season. There were no seeding suspensions during the season. Table 4-1 shows the dates and ground generator usage for the storm events, and Appendix B contains more detailed site usage data. Figure 4.1 shows the usage of generator hours during the season.

Precipitation and snowfall were generally near normal during the 2019-2020 winter season, with snow water equivalent for the Weber-Ogden River basin averaging about 99% of the median value on April 1st. The water year precipitation through April 1st averaged 91% of the normal (mean value) across the basin. The Provo River basin had corresponding April 1st averages of 104% of median snowpack and 88% of mean precipitation. Figures 4.2 to 4.4 are seasonal graphs for some SNOTEL sites in the target area.

Table 4-1
Storm dates and number of generators used, 2019-2020 season.

Storm No.	Date(s)	No. of Generators Used	No. of Hours
1	December 8	4	22.25
2	December 12-13	6	80
3	December 14	7	55.5
4	December 24-25	2	48
5	January 1-2	6	92.75
6	January 9	4	10.25
7	January 12-13	5	46.75
8	January 14	8	24
9	January 16-17	7	71
10	January 21-22	6	80.25
11	January 26-27	5	67
12	February 6-7	3	52.75
13	February 16-17	5	69.25
14	March 1	5	34
15	March 8	5	45.25
16	March 18	6	25.75
17	March 21	2	6
18	March 24-26	3	126
Season Total	---	---	956.75

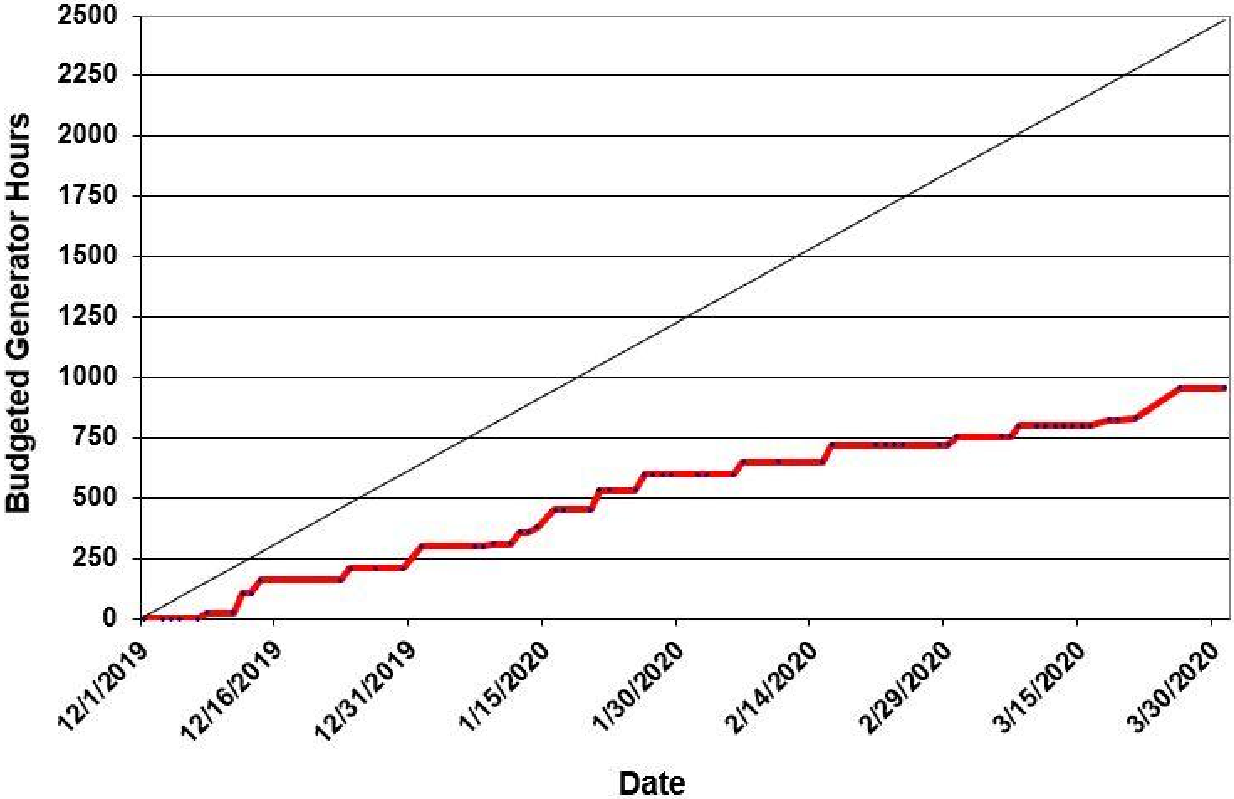


Figure 4.1 Seeding during the 2019-2020 season (red), in comparison to a linear usage of budgeted hours through the season (diagonal line)

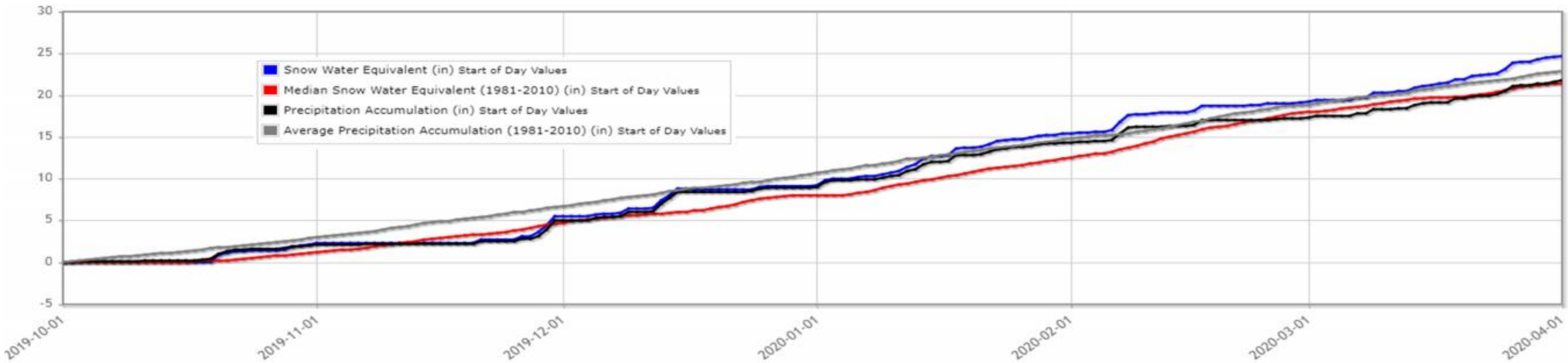


Figure 4.2 NRCS SNOTEL snow and precipitation plot for October 1st, 2019 through April 1st, 2020 for Trial Lake, UT.

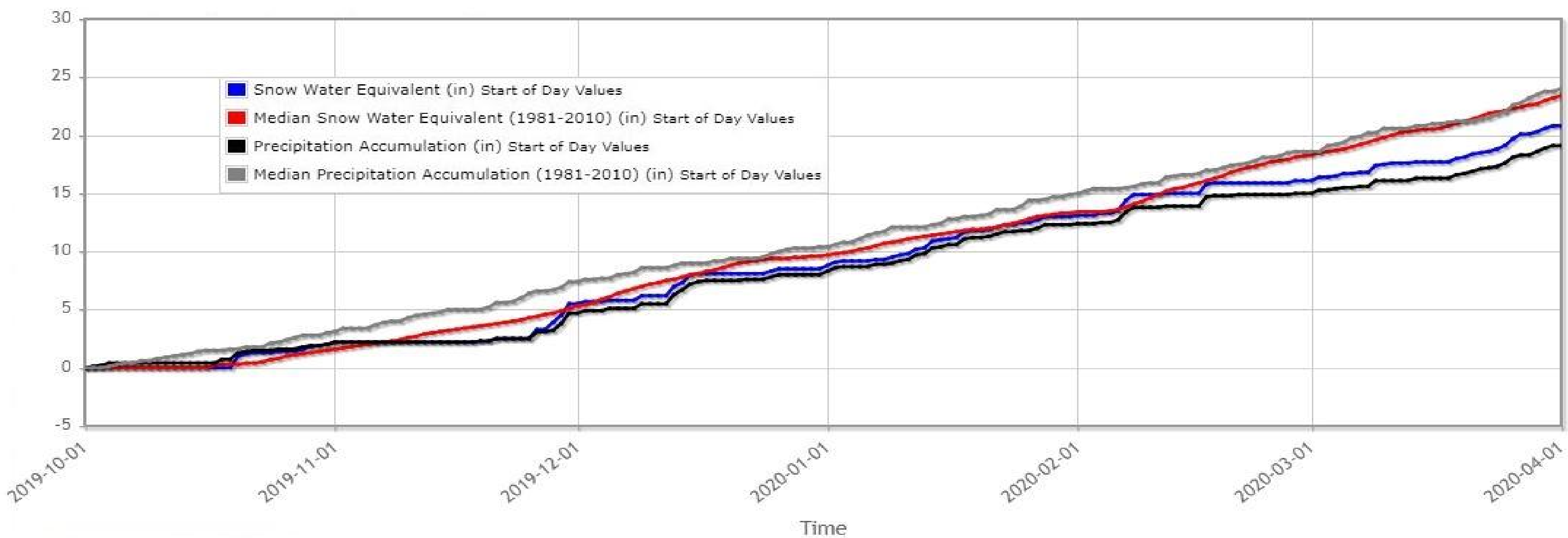


Figure 4.3 NRCS SNOTEL snow and precipitation plot for October 1st, 2019 through April 1st, 2020 for Chalk Creek #1, UT.

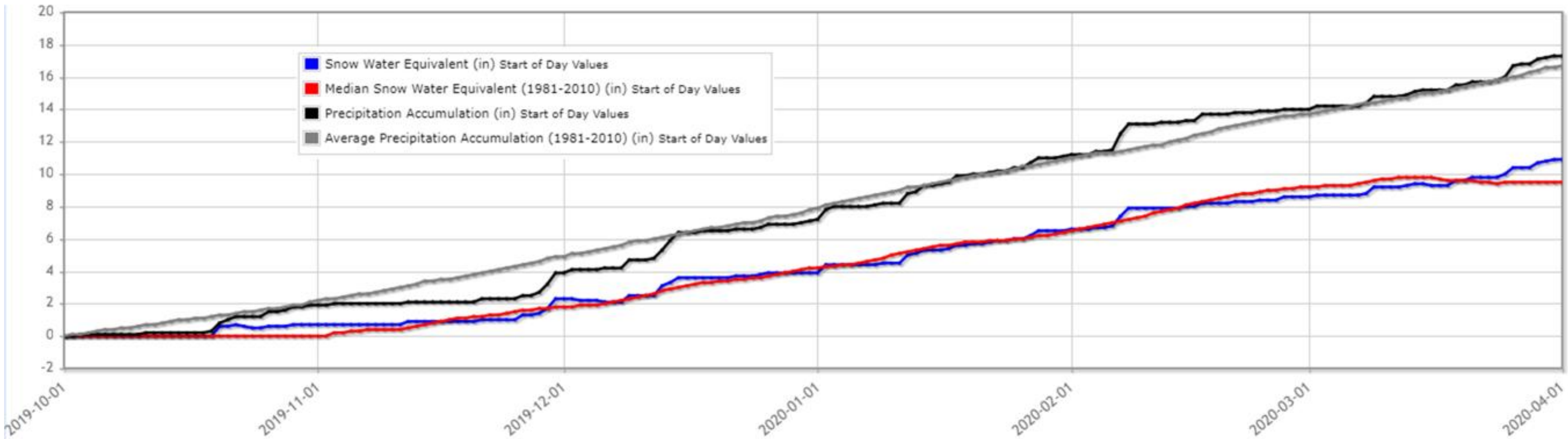


Figure 4.4 NRCS SNOTEL snow and precipitation plot for October 1st, 2019 through April 1st, 2020 for Beaver Divide, UT.

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

December 2019

December brought near to somewhat above normal precipitation and snowfall, with an active weather pattern particularly in the middle of the month. There were four seeded storm events in December. Figure 4.5 shows December 2019 precipitation across the region as a percentage of average (mean) monthly totals.

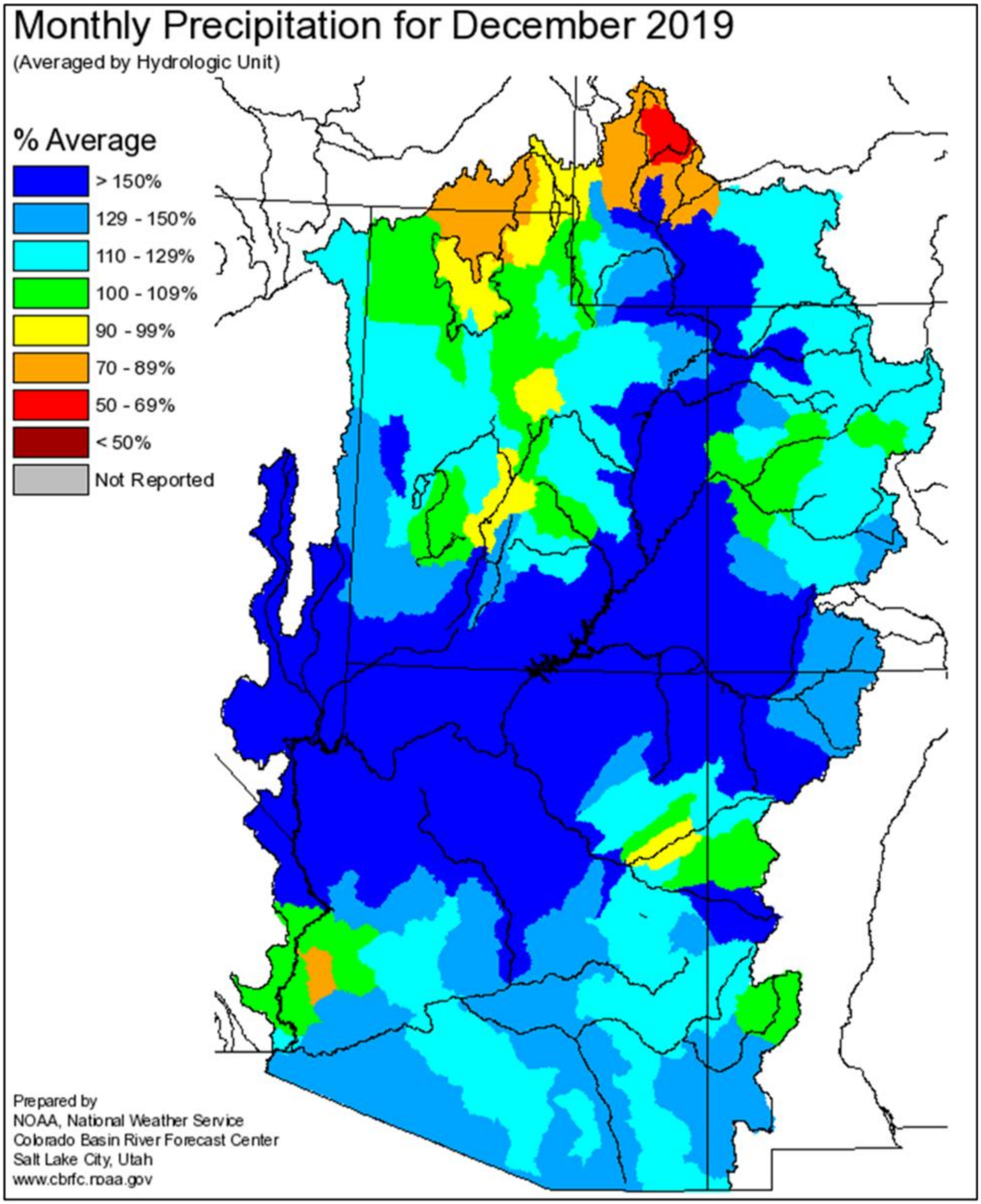


Figure 4.5 December 2019 precipitation, percent of normal

A brief seeding opportunity occurred on December 8th with a frontal passage, the first opportunity of the season. Seeding was conducted during the afternoon to early evening hours as winds shifted to the W-NW and temperatures cooled to below -5°C at 700 mb, with lower-level mixing improving through the day as well.

A period of very significant precipitation began on December 12th, with a moist westerly wind pattern and a 700 mb temperature near -5°C. Cloud types were unfavorable for seeding initially, although convective activity developed due to cooling aloft later in the day. Some convective cells even produced lightning in the Salt Lake City area over to the Western Uintas target area in the evening. Seeding was initiated in the early evening and continued overnight in westerly to west-northwest flow. Precipitation became very orographic in nature overnight, with some orographic "streamers" of precipitation visible in radar imagery downwind of terrain features. The event appeared very favorable for seeding operations, with precipitation of an inch or more of liquid water equivalent in much of the target area. Seeding ended on the morning of December 13th as precipitation had tapered off.

Another system moved into the area on the night of December 13th-14th, with increasing winds and warming temperatures at first. While this situation was not initially favorable for seeding, a shift from southwesterly to westerly wind and cooling temperatures, combined with a return of convective and orographic precipitation types, resulted in favorable seeding conditions on December 14th. Seeding operations continued through the day on December 14th with a 700-mb temperature near -8°C, ending around sunset as skies began to clear. The storm event was also fairly generous in terms of precipitation, with around a half inch to an inch in the target area.

A moist system moved into the area on December 24th, although some lower level stability and precipitation from a mainly high cloud deck were negative factors. Seeding was initiated at a couple sites that are essentially in the target area later in the day, and continued overnight in southwesterly flow. The pattern transitioned to cooler and more convective on December 25th, with light snow showers in westerly flow throughout the day. The 700-mb temperature was around -8° to -10°C on the 25th. Seeding ended later on December 25th, around sunset. Precipitation amounts ranged from about a quarter to half inch of liquid water equivalent.

January 2020

January precipitation amounts were quite variable locally, but generally near the average. Storm events occurred on a regular basis, with a total of seven seeded storm periods in January. Figure 4.6 shows January 2020 precipitation as a percentage of the monthly average.

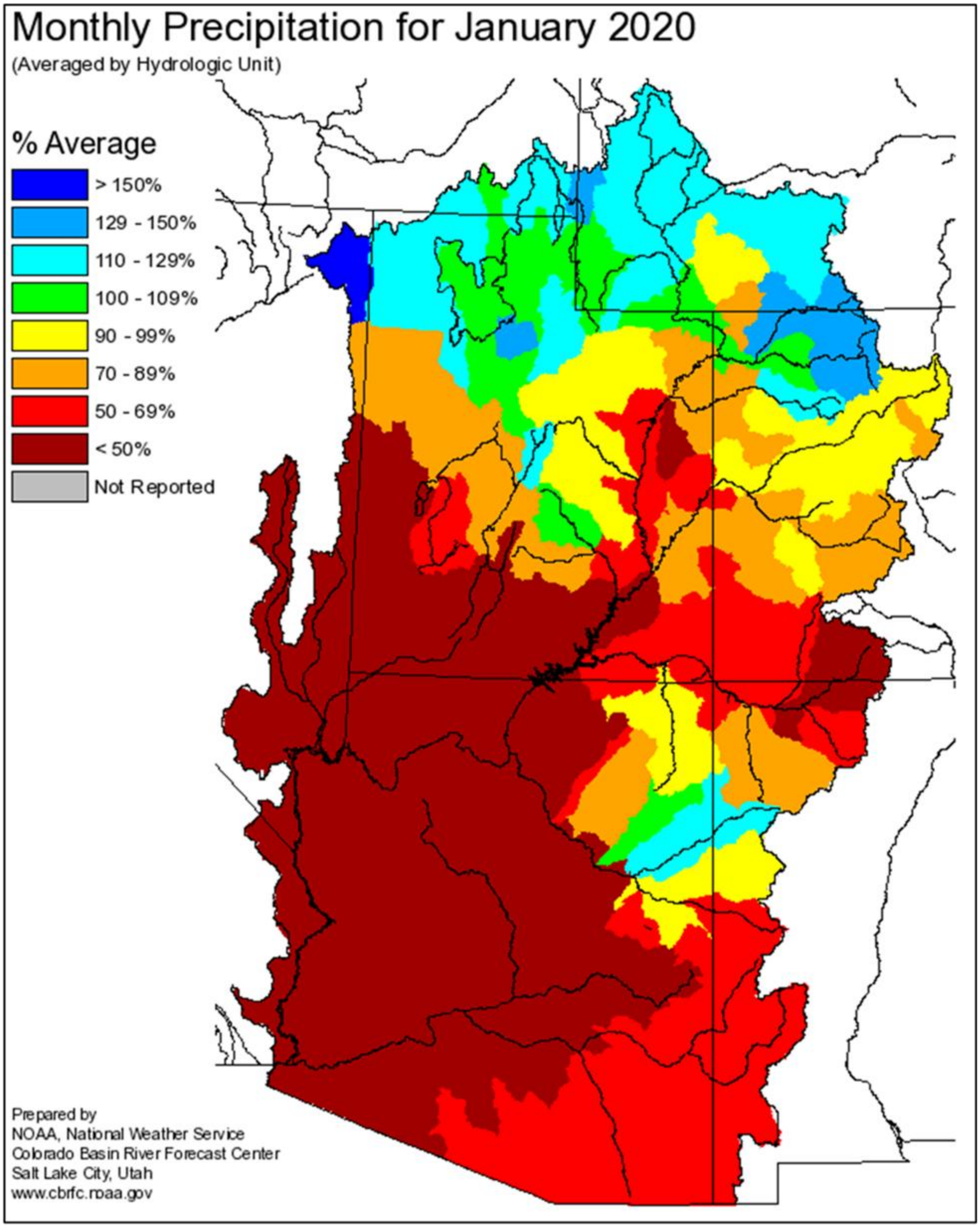


Figure 4.6 January 2020 precipitation, percent of normal

A fast-moving trough in strong northwesterly flow produced a seeding opportunity beginning on January 1st. Orographic and convective type precipitation continued overnight, with the 700-mb temperature falling from about -5° to -10°C during the time period. Precipitation totals were generally 0.5 – 1.0” from this storm event.

A brief seeding opportunity occurred on January 9th, with some weak convective showers in westerly flow during the afternoon hours and a 700-mb temperature near -12° C. Seeding was conducted from several sites for just a couple of hours. Precipitation totals were light, generally 0.1 – 0.2”.

Some light snowfall occurred on January 11th-12th from a higher cloud deck, but without any apparent supercooled water involved until late on the 12th. A few sites were activated on the evening of January 12th, with increasing southwesterly winds overnight and a 700-mb temperature near -10° to -11°C. Seeding operations were expanded on the morning of the 13th as winds were more westerly and some orographic effects were apparent on radar imagery, suggesting more favorable conditions for seeding. By midday, the cloud deck was thinning and seeding operations ended by early afternoon. More reports indicated a couple inches of snowfall, with roughly 0.2” of water equivalent at SNOTEL sites.

A large trough across the Pacific Northwest and northern Rockies pushed a cold front and snow band across northern half of Utah on January 14th. Snowfall began in the Western Uintas just ahead of the cold front early afternoon, with a pretty solid mid- level cloud deck containing some orographic and weakly convective elements. Seeding began just ahead of frontal passage by about 1300 MST. Winds were essentially westerly with most of this event, with 700-mb temps near -12°C. By 1700 MST, snowfall tailing off with mostly just higher clouds left, and seeding operations were ended in the early evening. Precipitation totals were mostly under about a quarter inch with this event.

A fast-moving cold front affected the area on the night of January 16th-17th, with snowfall continuing into much of the 17th. Winds were quite strong initially, and the 700-mb temperature fell from about -8° to -15°C on the 17th. Widespread snowfall in the morning became light convective type showers in the afternoon, with clouds appearing to have good SLW at least visually, despite fairly cold temperatures. Seeding operations ended by early evening with gradual clearing. Precipitation totals were quite variable, but generally between about 0.3 to 0.8” in the target area.

Seeding began on the evening of January 21st with light snowfall although questionable atmospheric mixing, with more sites added on the morning of January 22nd as conditions improved. A weak cold advection pattern produced weakly convective showers with the 700-mb temperature dropping to around -7°C. Seeding ended in the afternoon as showers tapered off with generally just a stratiform mid-level cloud deck observed. Precipitation totals were generally around 0.2 to 0.3" with this event.

A trough brought light to moderate precipitation and cooling temperatures on the night of January 26th-27th, with the 700-mb temperature cooling below -5°C after about midnight. Seeding was initiated late in the evening for overnight, and continued into January 27th with some light orographic type snow showers in northwesterly flow. Visually, clouds appeared to have good liquid water and the 700-mb temperature cooled to around -9°C on the 27th. Seeding continued until midday, when precipitation rapidly ended and operations were terminated as well. Precipitation totals with this system were about a quarter to half inch in the target area.

February 2020

Precipitation in February was well below the average across most of the area, with only a couple of seeding opportunities during the month.   Figure 4.7 shows the percentage of normal February precipitation across the region.

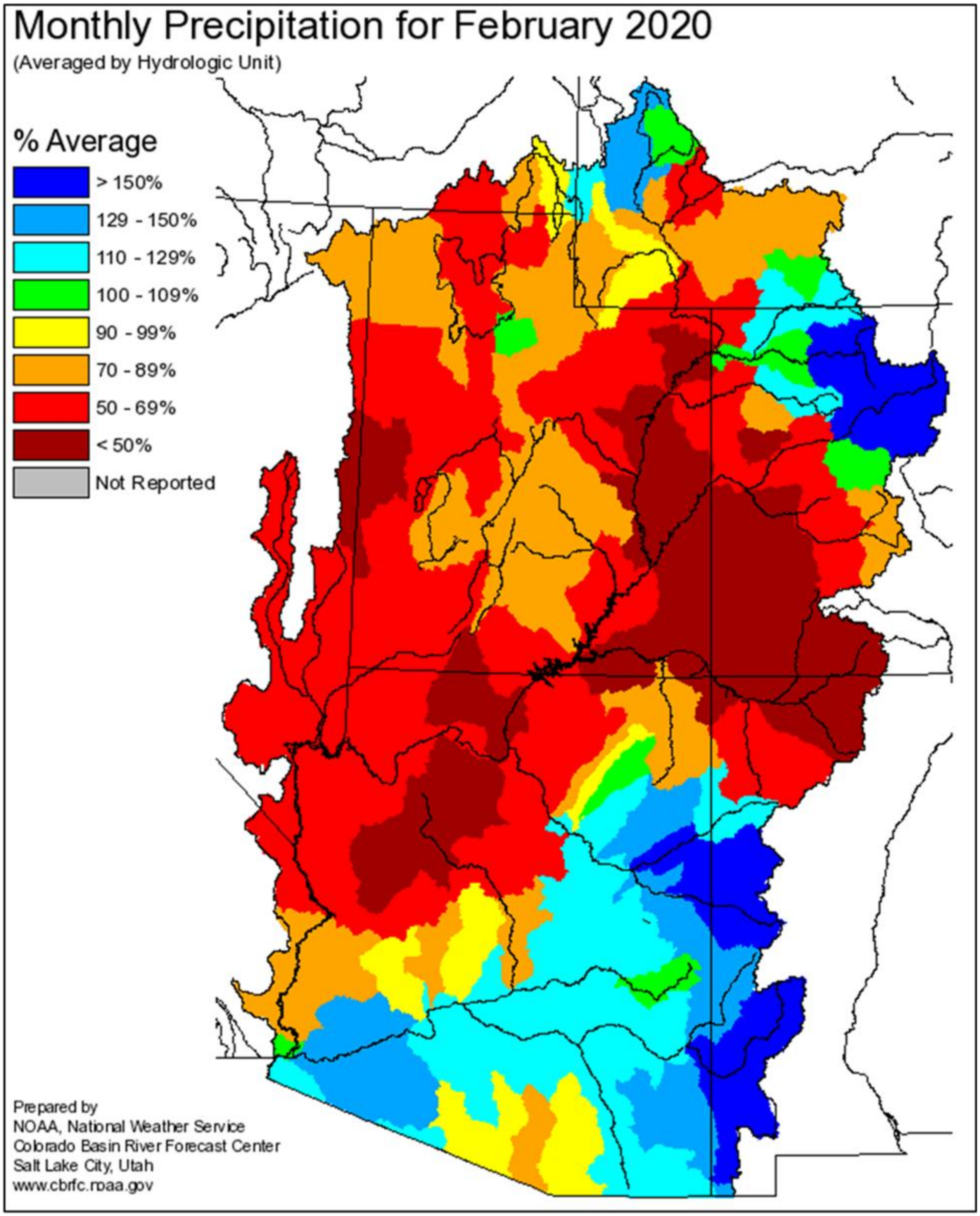


Figure 4.7 February 2020 precipitation, percent of normal

A strong plume of moisture on the eastern side of a ridge of high pressure produced a good deal of precipitation in a warm-advection pattern on February 6th-7th. The atmosphere was initially somewhat stable in the lower levels, but seeding began on the afternoon of February 6th as mixing improved in a strong northwesterly flow pattern. The 700-mb temperature began around -7°C on the 6th and gradually warmed to near/above -5°C on February 7th as the moisture plume remained over the area. Avalanche threats increased during this time period, with avalanche warnings issued for the backcountry. Although this in itself did not trigger any seeding suspension criteria, the situation was carefully monitored. Early on February 7th, major avalanche activity was reported in Little Cottonwood Canyon in the Salt Lake City area. Considering this and also warming temperatures aloft making conditions less conducive to seeding, it was decided to end seeding operations on the morning of February 7th. The February 6th-7th storm period as a whole brought between 1-2" of water equivalent to SNOTEL sites in the Western Uintas, with most sites receiving roughly 1.5" which was roughly half of the month's total precipitation.

The second most significant storm period in February occurred on February 16th-17th, which began with some light snowfall from a higher cloud deck on the 16th. Although conditions were initially unfavorable for seeding and there were no indications of liquid water, the situation improved on the night of February 16th-17th with a cold front moving into the area. Seeding was conducted in a westerly to northwesterly wind pattern overnight, with the 700-mb temperature falling from about -5° to -13°C with the frontal passage. Seeding ended on the morning of the 17th as skies cleared. Precipitation totals at most SNOTEL sites varied between about 0.5 and 0.9" of water equivalent.

March 2020

March was a near-normal month in terms of precipitation across most of the area, with storm systems affecting the area on a regular basis during the month. There were five seeded storm periods in March. Figure 4.8 shows the regional March precipitation as a percentage of normal.

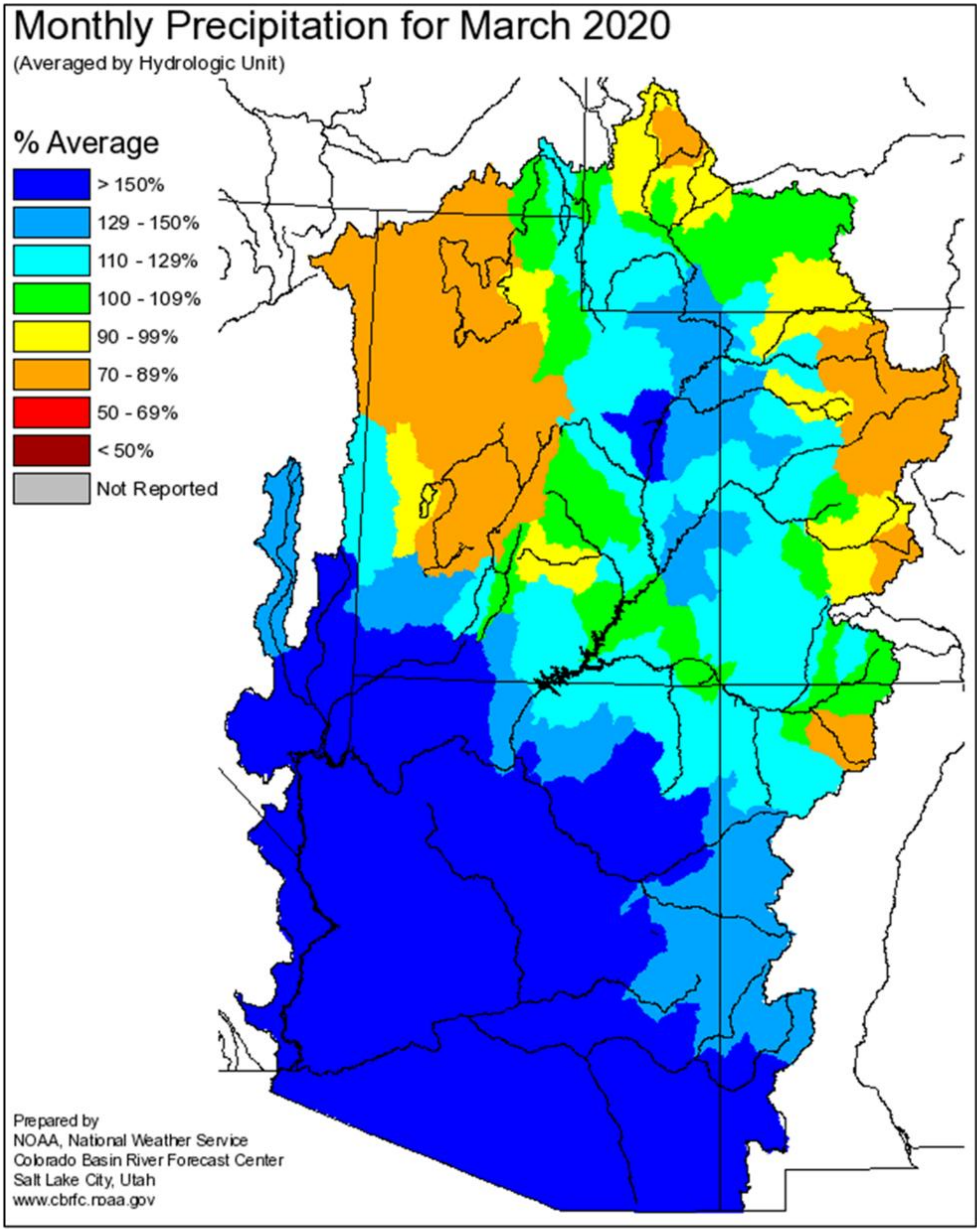


Figure 4.8 March 2020 precipitation, percent of normal

A deep trough developing over the western U.S. resulted in a seeding opportunity on March 1st. Seeding was conducted from the mid-morning through the afternoon hours in a west to northwest wind pattern, with the 700-mb temperature around -6° to -8°C. This system basically split with the main trough developing near California by later in the day, so the seeding opportunity was fairly brief. Most SNOTEL sites measured about 0.2" of water equivalent in this event.

A weakening frontal system brought showers to the area on March 8th in southwesterly flow, with the 700-mb temperature around -5°C. Seeding was conducted during the daytime hours from several sites, ending just prior to sunset as showers tapered off with loss of daytime heating. Precipitation amounts with this event were around 0.4 to 0.5" at most SNOTEL sites.

A complex system brought a fairly brief period of shower activity to the area on March 18th, with the 700-mb temperature around -5°C in southerly to southwesterly flow. Seeding began during the mid to late morning and ended during the early afternoon as precipitation ended and skies partially cleared. SNOTEL data showed amounts between 0.2 to 0.5" in the target area.

Some afternoon and early evening convective showers resulted in a brief seeding opportunity on March 21st, with the 700-mb temperature around -9°C. Precipitation amounts from these showers were in the 0.1 to 0.2" range.

A large trough centered over the Pacific Northwest brought periods of precipitation to Utah for several days in late March. Winds favored a southwesterly direction during most of this time period, and a few sites favorable for southwesterly flow were utilized for a fairly extended period from late on March 24th to early on the 26th. Temperatures were fairly warm initially also there are areas of significant convection. The 700-mb temperature did fall below -5°C on March 25th , and to as cold as near -10C on the 26th. Precipitation totals during this period amounted to between 0.5 to 1.0" of water equivalent in most of the target area. This was the last seeded event on the season, which ended on March 31st.

5.0 ASSESSMENT OF SEEDING EFFECTS

5.1 Background

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

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

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

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

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

5.2 Considerations in the Development of Target/Control Evaluations

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

There have been, and continue to be, multiple cloud seeding programs conducted in the State of Utah. As a consequence, potential control areas that are unaffected by cloud seeding are somewhat limited. This is complicated by the fact that the best correlated control sites are generally those closest to the target area, and SNOTEL measurement sites in Utah have likely been affected at some time by numerous historical and current seeding programs.

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

Another consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control site may be rejected due to poor data quality, which usually manifests itself in terms of missing data. We eliminate a site if it has significant amounts of missing data unless no better site can be found. If a significant measurement site is moved (more than a mile in any direction or a change in elevation of 100-200 feet) is indicated in the station records, the site or sites may be excluded from further consideration.

5.3 Evaluation of Precipitation in the Target Area

5.3.1 Target Precipitation Sites

Precipitation measurements were available from seven sites within and adjacent to the Western Uintas target area. These sites are shown in Figure 5.1, and are all higher elevation NRCS sites. The average elevation for the target area sites is about 8,660 feet above mean sea level (MSL). Location and elevation information for these target area sites is provided in Table 5-1.

Seeding has been conducted for periods of approximately four months during the program's history, although the exact seasonal period has varied somewhat. Ultimately, the period of December - March was chosen as being most representative of the most consistently seeded period. The target/control precipitation evaluation in some recent years has included only target sites 1-5 as shown above, because only the Weber River portion of the Western Uintas Program was active during the 2006 – 2011 water years. However, the SNOTEL sites selected to represent this portion of the program (Beaver Divide and Current Creek) are very likely impacted by seeding operations targeting the Weber River portion and the adjacent High Uintas seeding program as well, and the years when the Provo River portion of the program was inactive are also included in the evaluation using this set of 7 target sites. The entire seeding program was inactive during the 2012 water year, and thus that year is excluded from the average of the seeded season results.

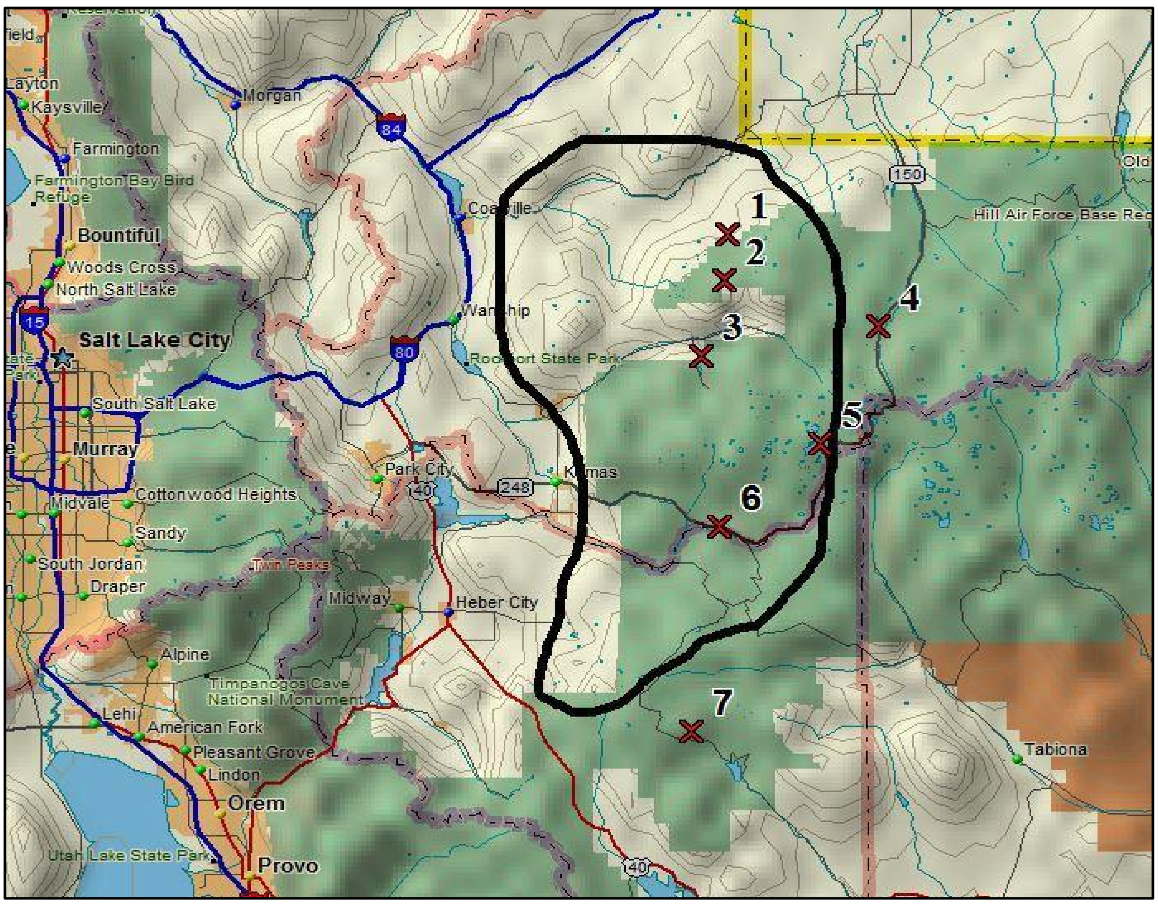


Figure 5.1 Western Uintas target area and precipitation gage sites (X).

Table 5-1
Target Area Precipitation Gauge Sites

Map Label	Site Name	Elev. (Ft)	Lat. (N)	Long. (W)
1	Chalk Creek #2	8,200	40° 54'	111° 04'
2	Chalk Creek #1	9,100	40° 51'	111° 04'
3	Smith & Morehouse	7,600	40° 47'	111° 06'
4	Hayden Fork	9,100	40° 48'	110° 53'
5	Trial Lake	9,960	40° 41'	110° 57'
6	Beaver Divide	8,280	40° 37’	111° 06’
7	Currant Creek	8,000	40° 21’	111° 05’

5.3.2 Precipitation Control Sites

The four control gauge sites are located in southern Idaho and northeastern Nevada, and are listed alphabetically in Table 5-2. The geographic relationship of the control area gauges to the target area is shown in Figure 5.2. Location and elevation information is provided in Table 5-2. The control group average elevation is 7,703 feet.

5.3.3 Regression Equation Development

Monthly precipitation values were totaled at each gauge in the control and target areas for the December-March period (the period that has most consistently been seeded in the western Uintas target area) in each of the historical non-seeded water years of 1982-1988 and 1997-2000 (11 seasons) and averages for each group were obtained. This period was selected to contain only data collected at SNOTEL sites (which began in the early 1980s) and to exclude the seasons of seeding for the western Uintas. A longer historical period would have been highly desirable since 11 seasons may well not be very representative of the longer term area climatology (i.e., this 11 year period could have occurred in a predominantly wet or dry cycle, such that a true climatological depiction may not be provided). There may be a tendency for over-estimation of target area precipitation in the historical period, since the period of 1997-2000 was seeded in northern Utah. This could have resulted in more precipitation in the Western Uintas during the historical period due to downwind effects and, therefore, less indication of seeding effects during the seeded years. The correlation coefficient (r) between the two groups for December-March was 0.88, suggesting that the estimator equation should provide good estimates of target area precipitation, in this case accounting for about 77% of the variance between the estimated and actual target area average precipitation when used for evaluation of seeding effect.

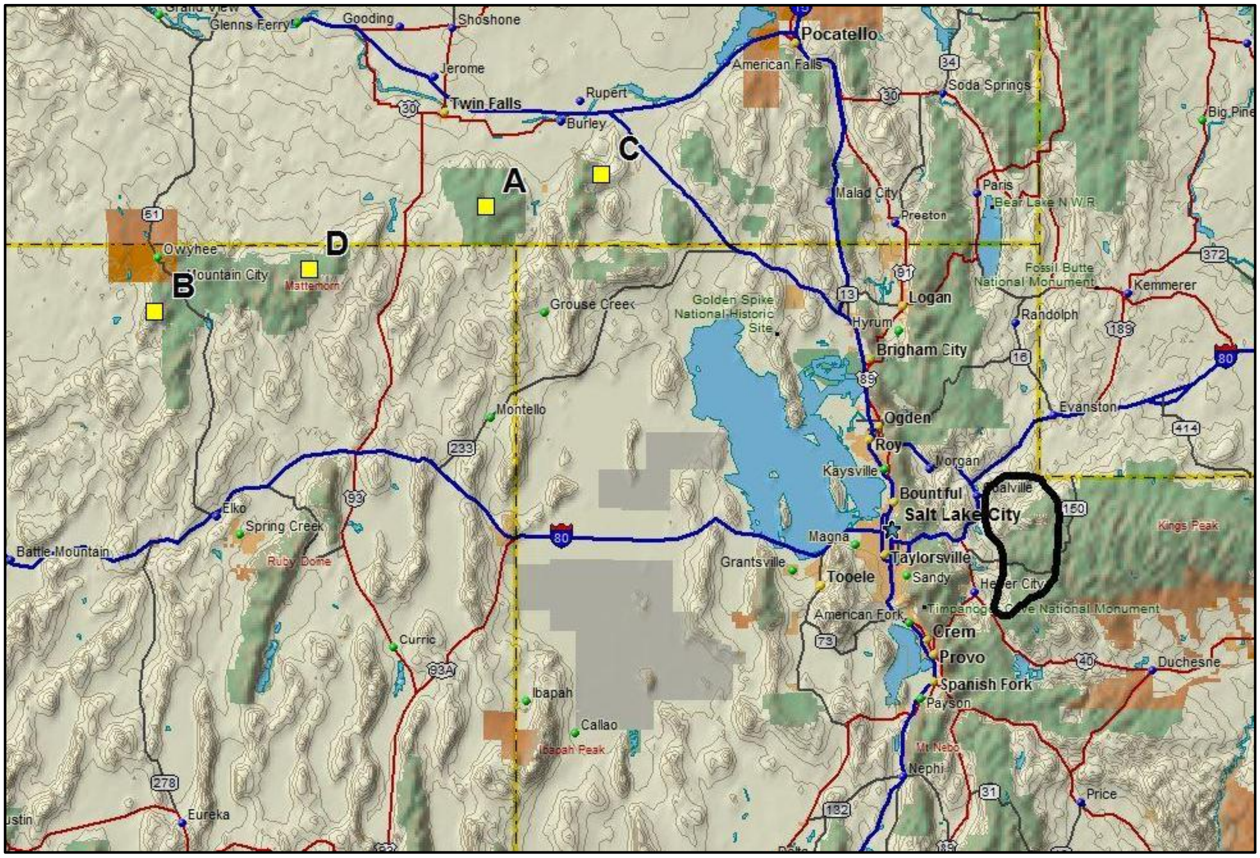


Figure 5.2 The Western Uintas target area (black outline) and control sites (yellow squares)

Table 5-2

Control Area Precipitation Gage Sites

Map Label	Site Name	Elev. (Ft)	Lat. (N)	Long. (W)
A	Bostetter R.S., ID	7,500	42°10'	114°11'
B	Fawn Creek #2, NV	7,000	41°42'	116°06'
C	Howell Canyon, ID	7,980	42°19'	113°37'
D	Pole Creek R.S., NV	8,330	41°52'	115°15'

The linear regression equation developed from the historical relationship between the control and target groups is as follows:

$$Y_C = 0.675 (X_O) + 3.46 \quad (1)$$

where Y_C is the calculated average target precipitation (inches) and X_O is the 4-station control average observed precipitation (inches) for the December-March period. The correlation coefficient is 0.88.

5.3.4 Precipitation Linear Regression Evaluation Results

When the observed average control precipitation (15.2 inches) for the December 2019 through March 2020 period was inserted in equation (1), the most probable average target area precipitation was calculated to be 13.7 inches. The actual observed average precipitation for the target group was 12.6 inches.

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

$$SE = R = Y_O / Y_C \quad (2)$$

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

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

$$SE = (Y_O - Y_C) / (Y_C \times 100) \quad (3)$$

From equation (2) the ratio of the average December-March observed precipitation to the average calculated precipitation in the target area was 0.92, which is 8% below the natural value predicted by the equation, e.g. not indicative of a seeding effect for the single season. However, single-season results carry almost no statistical significance, and should be viewed with extreme caution due to large seasonal variability in weather patterns that can either cancel out, or exaggerate, the seeding effects. The overall result from 25 seasons of seeding yielded an observed/predicted ratio of 1.00 (not indicative of an effect) for this precipitation evaluation, although the short historical period of only 11 seasons is a significant shortcoming of the precipitation analyses.

The results of the precipitation evaluations for this target/control set are summarized in Table 5-3. This table provides the results for each individual year as well as combined seeded years (December-March period). Table 5-3 contains many individual-season ratios less than 1.00. This might be misinterpreted to suggest that cloud seeding somehow reduced the amount of precipitation in the target area, or simply that it was ineffective. As the prediction technique is not exact, some ratios of less than 1.0 are to be expected **due to a variety of factors (e.g., contamination of the control areas, shortness of the historical period, and variations in precipitation patterns during individual seasons).**

Table 5-3

Summary of precipitation evaluations for <u>Linear Regression Analysis</u>
For the Western Uintas Program, December – March season
Correlation coefficient (r) for the historical period is 0.88.
Precipitation units are in inches of water.

Water Year	Sponsor Provo- P Weber- W	Control Precip	Target Observed	Target Predicted	Obs/Pred Ratio	Excess Precip
1989	P	15.03	13.37	13.60	0.98	-0.23
1990	P,W	9.85	11.59	10.10	1.15	1.48
1991	P,W	10.00	11.46	10.20	1.12	1.25
1992	P,W	5.15	6.01	6.93	0.87	-0.92
1993	P,W	17.13	17.83	15.01	1.19	2.82
1995	P,W	12.45	14.71	11.86	1.24	2.86
2001	P,W	9.23	8.64	9.68	0.89	-1.04
2002	P,W	13.45	10.37	12.53	0.83	-2.16
2003	P,W	9.93	9.61	10.15	0.95	-0.54
2004	P,W	14.58	10.36	13.29	0.78	-2.93
2005	P,W	11.60	14.99	11.28	1.33	3.70
2006	W	21.43	16.99	17.91	0.95	-0.93
2007	W	12.23	9.29	11.71	0.79	-2.42
2008	W	16.93	16.54	14.88	1.11	1.67
2009	W	16.20	14.67	14.39	1.02	0.28
2010	W	12.13	9.41	11.64	0.81	-2.22
2011	W	17.43	17.91	15.21	1.18	2.70
2013	P, W	13.35	9.03	12.46	0.72	-3.44
2014	P, W	14.48	13.20	13.22	1.00	-0.02
2015	P, W	11.08	7.99	10.93	0.73	-2.94
2016	P, W	17.80	13.16	15.47	0.85	-2.31
2017	P, W	21.30	23.00	17.83	1.29	5.17
2018	P, W	11.63	8.80	11.30	0.78	-2.50
2019	P, W	15.33	14.97	13.80	1.09	1.17
2020	P, W	15.20	12.60	13.71	0.92	-1.11
25 years		**13.79**	**12.66**	**12.72**	**1.00**	**-0.06**

A double ratio, which divides the overall average target/control precipitation during the seeded seasons by the corresponding ratio for the historical (non-seeded) seasons, was calculated utilizing the set of precipitation data. **This yielded a ratio of 1.03, which is a 3% precipitation increase** for the set of target sites relative to the control set that may be attributed to seeding. **The stronger statistical analyses for this particular seeding program are based on snowpack data and are summarized in Section 5.4.**

A multiple linear regression analysis has also been conducted for this same set of target/control precipitation data. In a multiple regression equation, the data from each of the control sites is utilized independently, instead of using an average value for all of the control sites. With this particular set of precipitation data, however, the multiple linear technique substantially increased the variability of the resulting ratios, compared to the linear regression. This is common in cases with a short historical regression period (only 11 seasons in this case), and in situations like this the multiple regression is not considered a reliable indicator of seeding effects on precipitation. However, for the snowpack evaluation for this program a multiple linear regression demonstrates strong correlation and also includes a significantly longer period of historic records.

5.4 Evaluation of Snow Water Content

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

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

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

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

5.4.1 Target/Control Sites and Regression Equation Development

The procedure was essentially the same as what was done for the precipitation evaluation, e.g., control and target area sites were selected, and average values for each were determined. Seven target area snow measurement sites were utilized for the Western Uintas Program, as shown in Figure 5.3. Table 5-4 provides the target area site names, elevations and locations of these sites. The average elevation of the target sites is 8,637 feet MSL.

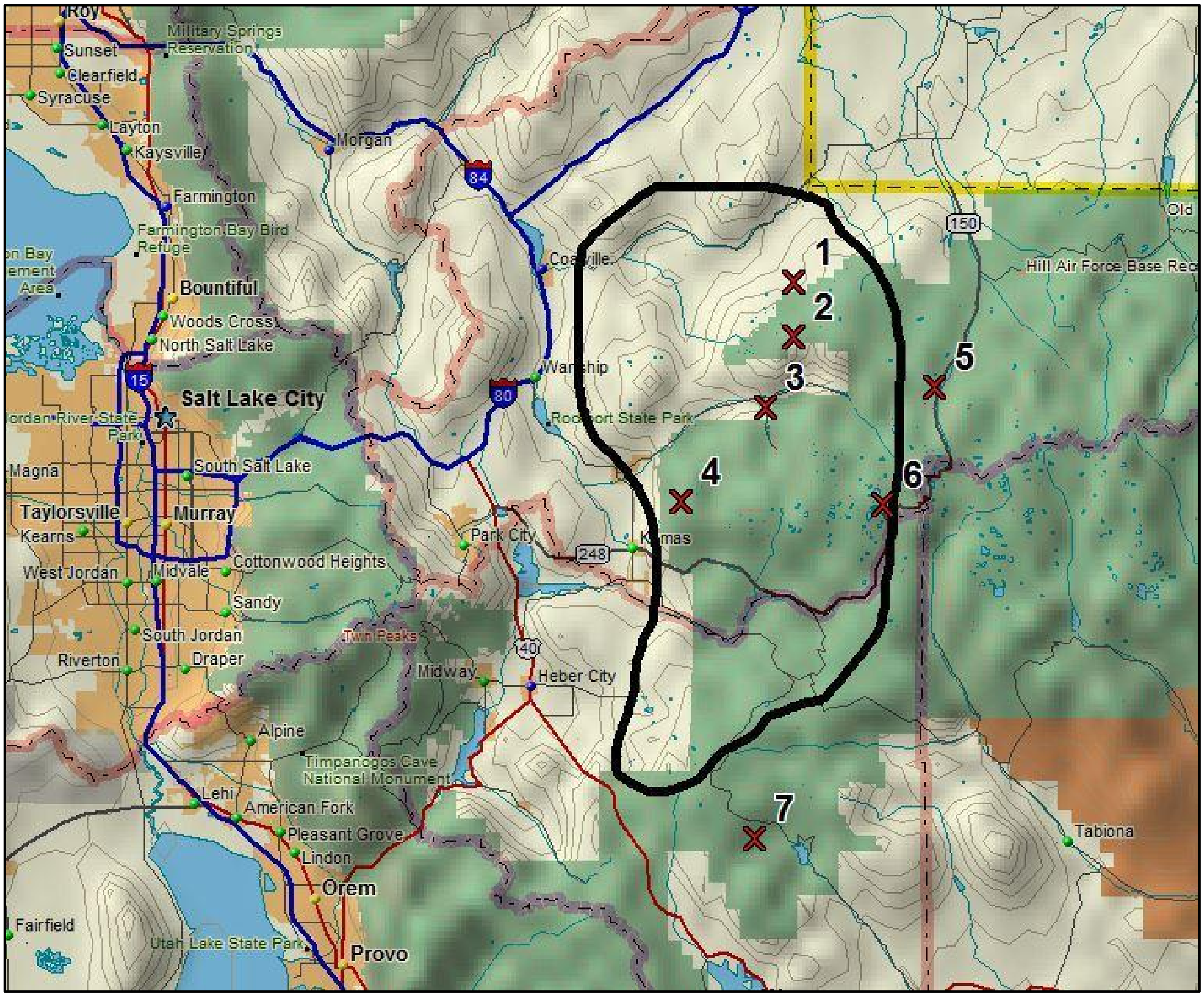


Figure 5.3 Western Uintas target area and snowpack target sites

Table 5-4
Target area snowpack sites

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

The five control sites are located in southern Idaho, northeastern Nevada and central Utah as shown in Figure 5.4. Control area site names, elevations and locations are provided in Table 5-5. The elevations of the control area sites average 6,887 feet (MSL). The non-seeded seasons were 1970-1988 and 1997-2000 (a total of 23 seasons). **Thus, many more historical seasons were available for the snow water content analyses than for precipitation, 23 versus 11 seasons. As a consequence, the snow water content analyses results are likely to be much more reliable than the precipitation analyses for this particular seeding program.**

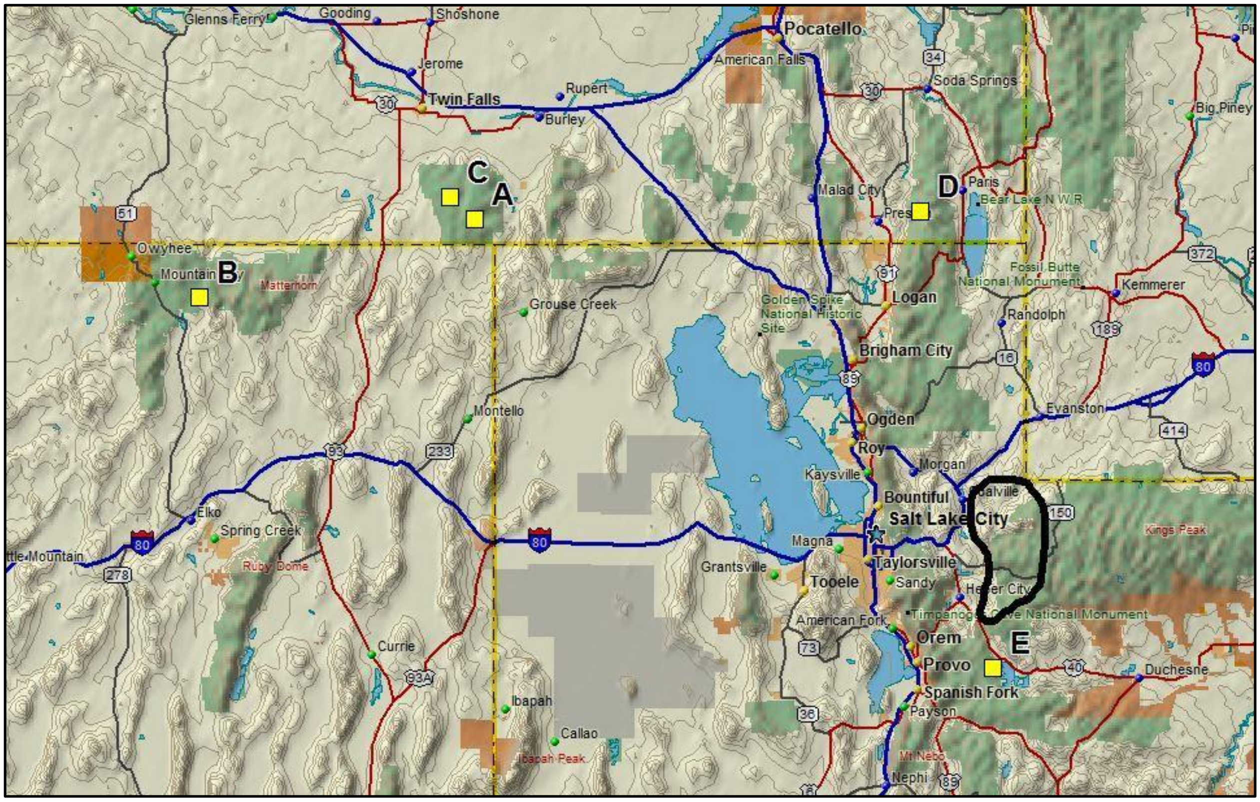


Figure 5.4 Western Uintas target area and snow control sites (squares)

Table 5-5
Control area snowpack sites

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

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

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

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

5.4.2 Linear Regression Snowpack Analysis

When the observed average control snow water content (14.8 inches) for April 1st, 2020 period was inserted in equation (1), the most probable average target area snow water content was calculated to be 17.3 inches. The actual observed average precipitation for the target group was 16.8 inches. This yields a single-season ratio of 0.97, which (for this single season) is itself not indicative of a seeding effect. As stated before, the single-season evaluation results carry very little statistical significance. The strength of the evaluation lies in the multi-year results as shown below.

The combined (23-year) snow water evaluation for April 1st , for the Western Uintas target sites, yields a ratio of 1.04. This long-term mean excludes water years 2004 and 2015 during which abnormal early snowmelt occurred, and thus only includes 23 seeded seasons instead of the 25 included in the precipitation evaluations. The implied 4% increase based on the snowpack evaluation is equivalent to an average of about 0.6 inches more water over the watersheds than might have occurred without the cloud seeding. The snowpack evaluation for the seeded water years is summarized in Table 5-6.

Table 5-6

Summary of April 1st snow water content evaluation for the Western Uintas Program, using the Linear Regression technique.
Correlation (r) for the historical period is 0.79.
Snowpack units are in inches of water equivalent.

Water Year	Control Average	Target Observed	Target Predicted	Obs/Pred Ratio	Excess Water (inches)
1989	17.22	18.04	19.12	0.94	-1.08
1990	6.94	14.79	11.50	1.29	3.28
1991	10.34	15.00	14.02	1.07	0.98
1992	3.44	10.29	8.91	1.15	1.38
1993	16.02	21.34	18.23	1.17	3.11
1995	11.96	18.43	15.22	1.21	3.21
2001	6.62	10.53	11.27	0.93	-0.74
2002	14.86	14.21	17.37	0.82	-3.16
2003	7.04	12.31	11.58	1.06	0.74
2005	14.26	21.09	16.93	1.25	4.16
2006	21.12	21.81	22.01	0.99	-0.20
2007	7.12	10.16	11.64	0.87	-1.48
2008	17.28	20.07	19.16	1.05	0.91
2009	14.06	17.17	16.78	1.02	0.39
2010	11.22	11.84	14.67	0.81	-2.83
2011	20.06	24.50	21.22	1.15	3.28
2013	9.14	10.69	13.13	0.81	-2.45
2014	11.16	16.61	14.63	1.14	1.98
2016	14.74	14.71	17.28	0.85	-2.57
2017	16.68	23.46	18.72	1.25	4.74
2018	7.40	10.29	11.84	0.87	-1.56
2019	18.44	21.64	20.02	1.08	1.62
2020	14.78	16.80	17.31	0.97	-0.51
23 years	**12.69**	**16.33**	**15.76**	**1.04**	**0.56**

5.4.3 Multiple Linear Regression Snowpack Analysis

A multiple linear regression analysis has been conducted for snowpack, and, in contrast to that for the precipitation data, exhibits much lower seasonal variability in the indicated observed/predicted ratios than does the corresponding linear regression. The r value is also much better than for the standard linear regression (0.90 vs. 0.79). This implies less background noise in this equation, and thus likely more reliable estimates of the true seeding effects. The results of the multiple regression snowpack analyses are provided in Table 5-7, implying about a 6% increase over the long term (obtained from the ratio of 1.06 shown in bold in the bottom row of that table).

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

Table 5-7
Summary of snow water content evaluation for the Western Uintas Program using the <u>multiple linear regression</u> technique. The correlation coefficient (r) for the historical period is 0.90. Snowpack units are inches of water equivalent.

Water Year	Magic Mtn, ID	Badger Gulch, ID	Willow Flat, ID	Big Bend, NV	Strawberry Div, UT	Target Observed Snowpack	Est Target Snow	Obs/Pred Ratio	Excess Water (inches)
1989	23.60	16.20	18.00	10.50	17.80	18.04	17.84	1.01	0.20
1990	10.20	7.70	4.00	0.00	12.80	14.79	13.45	1.10	1.34
1991	14.70	7.50	11.20	2.40	15.90	15.00	14.95	1.00	0.05
1992	3.60	3.00	3.70	0.00	6.90	10.29	9.05	1.14	1.24
1993	18.10	14.60	17.70	8.40	21.30	21.34	20.18	1.06	1.16
1995	15.70	10.40	12.90	3.90	16.90	18.43	16.52	1.12	1.91
2001	11.40	6.10	5.10	2.00	8.50	10.53	10.02	1.05	0.51
2002	20.90	15.80	14.30	10.40	12.90	14.21	14.88	0.96	-0.66
2003	10.60	4.20	8.10	2.00	10.30	12.31	10.71	1.15	1.61
2005	16.70	9.80	14.90	7.70	22.20	21.09	18.68	1.13	2.40
2006	28.20	18.20	21.00	14.50	23.70	21.81	21.03	1.04	0.78
2007	14.00	5.20	6.00	1.80	8.60	10.16	9.51	1.07	0.65
2008	20.00	16.80	19.00	11.60	19.00	20.07	19.16	1.05	0.91
2009	20.40	10.20	15.50	10.10	14.10	17.17	13.50	1.27	3.67
2010	15.70	11.20	10.80	8.40	10.00	11.84	11.97	0.99	-0.13
2011	21.80	15.40	24.60	13.80	24.70	24.50	21.82	1.12	2.68
2013	15.20	9.60	9.40	2.00	9.50	10.69	12.03	0.89	-1.34
2014	17.70	11.40	10.20	2.20	14.30	16.61	15.18	1.09	1.43
2016	22.40	14.70	14.80	9.50	12.30	14.71	14.11	1.04	0.61
2017	19.80	15.10	15.20	10.10	23.20	23.46	20.64	1.14	2.82
2018	12.70	6.90	7.10	2.70	7.60	10.29	9.79	1.05	0.49
2019	21.20	17.70	19.00	10.40	23.90	21.64	22.32	0.97	-0.67
2020	21.40	15.60	13.00	8.40	15.50	16.80	16.37	1.03	0.43
All	17.22	11.45	12.85	6.64	15.30	16.33	15.38	**1.06**	0.95

5.5 Summary of Evaluation Results

The cumulative statistical results from 25 seeded seasons included in the **precipitation** evaluation yields observed/predicted ratios of about 0.99 for the linear regression technique. Unfortunately, the precipitation analysis has a very short historical regression period of only 11 seasons (a set of 20 or more seasons is desired for improved long-term representativeness).

The April 1st **snowpack** analyses for 23 seeded seasons (2004 and 2015 were excluded) yield observed/predicted ratios of 1.04 (linear) and 1.06 (multiple linear). The results using April 1st snowpack imply average increases of roughly 4%-6%, which seems reasonable for this program, particularly in comparison to results of similar programs in the western U.S. The April 1st snowpack evaluations are considered more representative than the December-March precipitation evaluations due to a much longer historical period being available for the snow water versus precipitation evaluation (23 versus 11 seasons) and a stronger statistical correlation (i.e., r value of 0.90). Also of interest in the case of the snowpack evaluations is the much lower year-to-year variability observed in the results of the snowpack multiple linear evaluation, suggesting that this particular equation is likely the best predictor of the "expected" natural target area precipitation based on the available control site snowpack data. **This suggests a likely long-term average seeding effect in the neighborhood of 6% for this program.**

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

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

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

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

This situation was also considered in a study conducted by Givati and Rosenfeld (2004); they reported on an operational cloud seeding program being conducted in Israel, plus some areas in California that are exhibiting these pollution impacts. A quote from the Givati and Rosenfeld study is as follows: "In this study, we avoided addressing the possible confounding effects of the glaciogenic cloud seeding of the orographic clouds in both Israel and California. If seeding did enhance precipitation, the effects in the absence of seeding may have been larger than indicated in this study." **In other words, cloud seeding may potentially be offsetting the negative effects of air pollution on precipitation.** For example, if air pollution was reducing December through March precipitation by 10% and cloud seeding was increasing precipitation by 10%, the evaluations that we have been conducting for the Western Uintas may indicate no effect even though there actually was a 10% increase due to cloud seeding. And the corollary is that without cloud seeding, the drop in precipitation due to pollution effects might be more pronounced.

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

Conclusions

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

The cumulative evaluation results using the regular and multiple linear regression techniques based on April 1st snow water content, indicate an estimated 4% to 6% seasonal average increase These are considered to be the best, most credible (although perhaps still conservative) estimations of the true effects of the seeding program.

For the Western Uintas program, a 5% average increase would yield approximately ~0.8 inches of additional water over the target area. The target area comprises approximately 600 square miles. An average 0.8 inches of augmented water across the target would yield approximately 25,600 additional acre-feet of runoff. Using an estimated average current cost of conducting the seeding program, during a winter season presenting average seeding opportunity, of approximately $77,000, the cost of producing the additional runoff via cloud seeding would be approximately $3.01 per acre-foot.

6.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Precipitation and snowfall were generally near normal during the 2019-2020 winter season, with water year precipitation totals on April 1st averaging about 91% of the average (mean). SNOTEL sites had an April 1st snowpack averaging 99% of the long-term median. Similar snowpack/precipitation percentages for the Provo River Basin on April 1 were 104% and 88%, respectively. For the 2019-2020 winter season, a total of 18 storm periods were seeded, during a four-month operational period which began December 1st, 2019 and continued through March 31st, 2020. The cloud seeding generators were operated for a cumulative total of 956.75 hours.

It is of note that following the completion of this program, Utah experienced an uncharacteristically dry April and May. The result was the 3rd driest spring on record, leaving most of Utah in a state of moderate drought. Dry fall conditions also worked to reduce spring runoff as the groundwater absorption was above average.

Evaluations of the effectiveness of the cloud seeding program were made for both the past winter season and for the 25 seeded winter seasons combined. These evaluations utilized records from U.S. government sponsored data collection networks within and surrounding the seeded "target" area. Analyses of the effects of seeding on high elevation <u>precipitation</u> and April 1st <u>snow water content</u> in the target area have been conducted for this seeding program utilizing a target/control comparison technique.

Analyses Using Precipitation Data

Precipitation data during 11 historical December-March seasons (without any cloud seeding activities) at gauge sites in the intended target area and not seeded (control) areas were compiled, and averages determined. These data were utilized to develop mathematical relationships, using both single and multiple linear regression techniques, between the control area precipitation and the average precipitation observed at the target sites. These relationships were then applied to the seeded December-March seasons to calculate the expected (most probable) target area natural precipitation. These calculated amounts were then compared to the observed amounts in the target area. The multiple regression analysis utilized the same target and control stations as the standard linear regression analysis. These standard and multiple regression linear analyses using precipitation data suffer from the effects of a short historical period (11 seasons).

The precipitation analysis results applied to all 25 seeded seasons yielded a composite observed/predicted ratio of 1.00 using the linear regression technique, which is not indicative of a seeding effect using this estimation technique with precipitation data. A separate double-ratio analysis of the precipitation data, which consists of the target/control ratio for the seeded seasons divided by the corresponding ratio for the historical seasons, yields a ratio of 1.03. This is suggestive of a 3% increase on precipitation.

The analyses using snow water content (as reviewed hereafter) are based on a much longer and more complete historical data set, and are therefore more statistically reliable.

Analyses Using Snow Water Content Data

Linear and multiple linear analyses were performed using NRCS April 1st snow water content data. The April 1 snowpack analyses for 23 combined seeded seasons (Water Years 2004 and 2015 excluded due to very abnormal early snowmelt) suggest a 4% average seasonal increase using the simple linear regression technique and 6% using the multiple linear regression technique.

NAWC considers the snowpack analyses to be much more representative than the precipitation analyses for this particular program, due to the longer historical unseeded period from which the target/control regression equations could be developed (e.g., 23 historical seasons versus 11). The multiple linear regression technique using the April 1st snowpack data (the evaluation with a 6% increase indication) has much better signal to noise ratio than the other analyses that have been conducted for this program, yielding lower year to year variability in the results. As discussed in Section 4.0 and again summarized below, there are a variety of factors that are likely to have a negative impact on the evaluation results (although not on the actual seeding effectiveness) and may result in the seeding increase estimates being overly conservative. Although a higher result of 1.13 (suggesting a 13% increase) was obtained from the snowpack data using a double-ratio method, we consider the 6% increase indication from the multiple linear equation to be the most reliable for this seeding program.

Further Discussion

It is challenging to perform a solidly representative evaluation (utilizing either snowpack or precipitation data) for the project target area for the following reasons:

1) There is a lack of well-correlated control sites due to ongoing seeding programs being conducted in other areas of northern and central Utah and northeastern Nevada. Using data from these areas (which we have basically been forced to do because of the need to achieve high correlations between

control and target sites) can potentially have the effect of raising predicted target area precipitation, thus lowering the indicated effects of seeding. We look at this as a possible seeding contamination effect at some of the control sites).

2) Using farther removed sites as controls to avoid some of these contamination concerns results in lower correlations, and therefore a reduced ability to accurately estimate the target area natural precipitation or snow water content.

3) There is a limited historical (not seeded) period of 11 seasons available for the development of precipitation target and control analyses. **A longer period of 20-25 seasons would be highly desirable. A longer historical non-seeded period is available for the snow water content regression equations and as a consequence *these snowpack evaluations are considered more representative than the precipitation evaluations*.**

4) The duration of the actual seeded period has varied in some seasons from the standardized period of December - March used in the precipitation evaluations.

5) Based upon research published in peer-reviewed journals, winter precipitation has declined in mountainous areas downwind of major cities in the western United States. Apparently, these declines in precipitation are due to air pollution generated by upwind cities. This effect is evident for some precipitation sites in the western Uintas target area (Griffith et al., 2005). The pollution-induced precipitation reduction would likely have the impact of counteracting the real seeding effects.

The Bottom Line

Because evaluation of the Western Uintas Program is especially challenging, the difficulties involved have been thoroughly described in this report. However, with those realities and their potential impacts summarized, we offer the following summary statements regarding the seeding project effectiveness.

<u>The cumulative evaluation results using the regular and multiple linear regression techniques based on April 1st snow water contents, indicating an estimated</u>

4% to 6% seasonal average increase, are considered to be a reasonable (and conservative) estimate of the true effects of the seeding program.

For the Western Uintas seeding program, a (possibly conservative) 5% average increase in snow water content yields approximately 0.8 inches of additional water over the entire project target area. The target area comprises approximately 600 square miles. An average 0.8 inches of augmented water across the target would yield approximately 25,600 additional acre-feet of runoff. Using $77,000 as an estimated average current cost of conducting the seeding program during a winter season, the cost of producing the additional runoff via cloud seeding is approximately $3.01 per acre-foot.

The value of additional runoff and recharge that can be generated from the target area is relatively high since this watershed provides streamflow that is used to meet municipal water supply requirements. Therefore, even rather modest percentage increases in target area precipitation are likely to be very beneficial when the value of the additional streamflow and recharge are compared to the cost of conducting the program.

We recommend to our clients that they consider conducting cloud seeding programs on a routine basis each year. This has proven to be very effective in southern and central Utah, where operational cloud seeding has been conducted for over 40 winter seasons in some areas. We recommend this overall approach for several reasons:

- No one can accurately predict if precipitation during the coming winter season will be above or below normal. Having a cloud seeding program already operational will take advantage of each seeding opportunity. Seeded wet years will provide reservoir recharge to help sustain water availability during drier years.

- In a best-case scenario, cloud seeding will increase precipitation by upwards of 10%. This is generally not enough to mitigate the long term implications of a dry winter, unless seeding has been continuously augmenting reservoir levels, in wetter years.

- Seeding in normal to above normal water years will result in a larger precipitation increase, which may provide additional carryover storage in surface reservoirs or underground aquifers that can be drawn from during dry years.

- Conducting cloud seeding programs only after drought conditions are encountered may mean fewer cloud seeding opportunities, leading to less additional precipitation being generated by a cloud seeding program.

We believe the Western Uintas cloud seeding program is meeting its stated objective of augmenting the precipitation in the target area in a highly cost-effective manner. It is recommended that the program be continued, to provide additional water for increasing water demand.

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APPENDIX A

UTAH WINTER CLOUD SEEDING SUSPENSION CRITERIA

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

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

1. Excess snowpack accumulation

2. Rain-induced winter flooding

3. Severe weather

1. Excess Snowpack Accumulation

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

Project & Basin	Critical Streamflow Volume (Acft) & USGS Streamgage	SNOTEL Station	SWE Value Corresponding to the Critical Flow								Ranking of SNOTEL Stations
			Jan 1 (in.)	Jan 1 (%)	Feb 1 (in.)	Feb 1 (in %)	March 1 (in.)	March 1 (in %)	April 1 (in.)	April 1 (in %)	
1. Northern Utah	185,208	Franklin Basin, Idaho	19.50	190.84	27.14	165.31	34.35	154.71	41.56	153.60	1
Logan at Logan	USGS 10109000	Tony Grove	28.73	205.94	39.44	175.56	48.06	160.38	56.34	156.56	2
		Bug Lake	17.08	218.82	21.91	180.34	26.72	165.25	31.65	162.70	3
		Average	**21.80**	**205.20**	**29.50**	**173.70**	**36.40**	**160.10**	**43.20**	**157.60**	
Weber near Oakley	176,179	Chalk Creek #1	10.09	173.13	14.73	153.66	28.77	149.85	34.15	143.41	1
	USGS 10128500	Trial Lake	20.15	207.44	26.33	180.55	33.55	173.27	38.54	162.28	2
		Smith Morehouse	10.06	186.34	13.69	157.60	17.36	146.52	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 -	USGS 10011500	Trial Lake	20.07	206.54	26.56	182.26	33.68	173.94	38.49	162.05	2
Wyoming state line		Hayden Fork	12.41	197.65	17.06	175.83	21.03	160.98	20.90	146.02	3
		Average	**14.60**	**202.30**	**20.00**	**184.10**	**24.10**	**160.80**	**29.40**	**149.10**	
Duchesne near Tabiona	140,976	Strawberry Divide	6.92	239.23	10.87	199.25	26.77	178.78	29.75	179.05	1
	USGS 09277500	Daniels-strawberry	16.07	248.12	21.59	202.44	27.82	190.54	29.89	192.75	2
		Smith Morehouse	10.61	196.64	14.95	172.41	18.82	158.83	22.22	168.26	3
		Rock Creek	8.76	230.02	12.31	219.65	15.88	205.68	16.41	209.06	4
		Average	**10.60**	**228.50**	**14.90**	**198.50**	**22.30**	**183.50**	**24.60**	**187.30**	
Provo near woodland	183,845	Trial Lake	22.98	236.53	27.78	190.63	35.23	181.59	31.44	132.39	1
	USGS 09277500	Beaver Divide	10.29	210.39	14.11	179.49	17.45	170.83	20.18	200.3	2
		Average	**16.70**	**223.50**	**20.90**	**185.10**	**26.30**	**176.20**	**25.80**	**166.40**	
3. Central & Southern	120,473	Castle Valley	12.23	244.05	16.96	203.04	22.22	187.68	26.30	180.00	1
Sevier near Hatch	USGS 10174500	Harris Flat	8.71	298.76	15.25	273.59	24.16	222.99	21.15	209.77	2
		Farnsworth Lake	17.25	218.10	20.96	185.95	27.05	182.24	32.93	167.03	3
		Average	**12.80**	**253.70**	**17.70**	**220.90**	**24.50**	**197.70**	**26.80**	**185.60**	
Coal Creek near	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	5,426	Rocky Basin-settlemnt	19.09	205.33	23.75	174.14	32.11	171.39	40.01	167.51	1
Grantsville	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	11,620	Gardner Peak	13.00	293.90	16.82	172.15	21.70	167.36	24.45	163.95	1
Reservoir	USGS 09409100	**Average**	**13.00**	**293.90**	**16.80**	**172.10**	**21.70**	**167.40**	**24.50**	**164.00**	
		Utah State Average (%)		**230**		**197**		**183**		**178**	
		Standard Deviation		**42**		**38**		**35**		**42**	
		Upper 95%		**248**		**213**		**199**		**196**	
		Lower 95%		**212**		**180**		**168**		**160**	

Snowpack-related suspension considerations will be assessed on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne River, Price-San Rafael, Dirty Devil, South Eastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. The Weber-Ogden and Provo River – Utah Lake – Jordan River criteria apply to suspension considerations for the Western Uintas project. Since SNOTEL observations are available on a daily basis, suspensions (and cancellation of suspensions) can be made on a daily basis using linear interpolation of the first of month criteria. For the Western Uintas, four SNOTEL sites (Chalk Creek #1, Trial Lake, Smith and Morehouse, and Rock Creek) have date-specific snow water equivalent criteria on which suspension decisions can be based.

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

2. Rain-induced Winter Floods

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

3. Severe Weather

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

- **Snow Advisory** - This product is issued by the NWS when four to twelve inches of snow in 12 hours, or six to eighteen inches in 24 hours, are forecast to accumulate in mountainous regions above 7000 feet. Lower threshold criteria (in terms of the number of inches of snow) are issued for valleys and mountain valleys below 7000 feet.

- **Heavy Snow Warning** - This is issued by the NWS when it expects snow accumulations of twelve inches or more per 12-hour period or eighteen inches or more per 24-hour period in mountainous areas above 7000 feet. Lower criteria are used for valleys and mountain valleys below 7000 feet.

- **Winter Storm Warning** - This is issued by the NWS when it expects heavy snow warning criteria to be met, along with strong winds/wind chill or freezing precipitation.

- **Flash Flood Warnings** - This is issued by the NWS when flash flooding is imminent or in progress. In the Intermountain West, these warnings are generally issued relative to, but are not limited to, fall or spring convective systems.

Seeding operations may be suspended whenever the NWS issues a weather warning for or adjacent to any target area. Since the objective of the cloud seeding program is to increase winter snowfall in the mountainous areas of the state, operations will typically not be suspended when Heavy Snow or 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

PRECIPITATION AND SNOWPACK EVALUATION DATA/RESULTS

Table B-1
Generator Hours – Western Uintas, 2019-2020
Storms 1-10

Storm	1	2	3	4	5	6	7	8	9	10
Date	**Dec 8**	**Dec 12-13**	**Dec 14**	**Dec 24-25**	**Jan 1-2**	**Jan 9**	**Jan 12-13**	**Jan 14**	**Jan 16-17**	**Jan 21-22**
SITE										
W1										
W2										
W3		12.5	8.25		16.25			4.5	6.5	17.5
W4					0					17.5
W6	6	13.75	8.25		16.5	3	6.25	4.5	10	2.5
W7	6.25	13.75	7.5		16.5	2	6.25	3.25	7.5	17.5
W8	5	12.75	8.25		17	2.5	5	2.5	10.5	7.5
W9	5	14	7.75	24	14.5	2.75	14.75	3	15.5	17.75
W10			7.75	24					0	
W11								3.25	10	
W12							14.5			
W14		13.25	7.75		12			3	11	
Storm Total	**22.25**	**80**	**55.5**	**48**	**92.75**	**10.25**	**46.75**	**24**	**71**	**80.25**

Table B-2
Generator Hours – Western Uintas, 2019-2020
Storms 11-18

Storm	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	
Date	**Jan 26-27**	**Feb 6-7**	**Feb 16-17**	**Mar 1**	**Mar 8**	**Mar 18**	**Mar 21**	**Mar 24-26**	**Site Totals**
SITE									
W1		17.75							17.75
W2			14						14
W3	8	17		8					98.5
W4	3.75		14	8					43.25
W6			14	5.75	10.5	4			105
W7	15.75		13.5		10.75	4			124.5
W8	14.5						3	44	132.5
W9	9		13.75	6.5	10.5	3		44	205.75
W10						4.25			36
W11									13.25
W12					3	4.25	3	38	62.75
W14	16	18		5.75	10.5	6.25			103.5
Storm Total	**67**	**52.75**	**69.25**	**34**	**45.25**	**25.75**	**6**	**126**	

APPENDIX C

PRECIPITATION AND SNOWPACK EVALUATION DATA/RESULTS

Western Uintas December – March Precipitation, Linear Regression

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:					
1980	21.45	19.89	17.93	1.11	1.96
1981	9.55	11.53	9.90	1.16	1.63
1982	21.23	20.44	17.78	1.15	2.66
1983	16.45	13.03	14.56	0.90	-1.53
1984	20.43	13.81	17.24	0.80	-3.42
1985	9.63	11.47	9.95	1.15	1.52
1986	18.55	17.23	15.97	1.08	1.26
1987	8.73	8.41	9.34	0.90	-0.93
1988	10.88	10.77	10.79	1.00	-0.02
1997	20.68	17.74	17.41	1.02	0.34
1998	16.48	14.34	14.57	0.98	-0.23
1999	14.25	12.64	13.07	0.97	-0.43
2000	15.15	14.47	13.68	1.06	0.79
Mean	15.68	14.03	14.03	1.00	0.00

Seeded period:

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

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
2018	11.63	8.80	11.30	0.78	-2.50
2019	15.33	14.97	13.80	1.09	1.17
2020	15.20	12.60	13.71	0.92	-1.11
Mean	13.79	12.66	12.72	**1.00**	**-0.06**

* No seeding in target areas
** Seeding in Weber Basin but not in Provo R Basin

SUMMARY OUTPUT

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

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

Western Uintas April 1 Snowpack, Linear Regression

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:					
1970	16.14	16.21	18.32	0.89	-2.11
1971	18.66	21.43	20.19	1.06	1.24
1972	19.18	18.17	20.57	0.88	-2.40
1973	16.02	16.61	18.23	0.91	-1.62
1974	18.42	16.77	20.01	0.84	-3.24
1975	20.08	19.97	21.24	0.94	-1.27
1976	17.46	17.33	19.30	0.90	-1.97
1977	6.24	8.97	10.98	0.82	-2.01
1978	16.18	19.23	18.35	1.05	0.88
1979	17.40	17.80	19.25	0.92	-1.45
1980	19.86	25.26	21.08	1.20	4.18
1981	8.38	12.66	12.57	1.01	0.09
1982	21.08	23.50	21.98	1.07	1.52
1983	18.42	20.90	20.01	1.04	0.89
1984	24.80	22.01	24.74	0.89	-2.72
1985	16.06	21.44	18.26	1.17	3.18
1986	15.84	25.73	18.10	1.42	7.63
1987	8.08	13.97	12.35	1.13	1.62
1988	11.42	14.23	14.82	0.96	-0.59
1997	19.72	22.41	20.97	1.07	1.44
1998	14.30	16.39	16.96	0.97	-0.57
1999	13.34	14.86	16.24	0.91	-1.39
2000	13.90	15.41	16.66	0.93	-1.25
Mean	16.13	18.32	18.31	1.00	0.00

Seeded period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1989	17.22	18.04	19.12	0.94	-1.08
1990	6.94	14.79	11.50	1.29	3.28
1991	10.34	15.00	14.02	1.07	0.98
1992	3.44	10.29	8.91	1.15	1.38
1993	16.02	21.34	18.23	1.17	3.11
1994*	8.42	13.31	12.60	1.06	0.72
1995	11.96	18.43	15.22	1.21	3.21
1996*	16.96	22.21	18.93	1.17	3.29
2001	6.62	10.53	11.27	0.93	-0.74
2002	14.86	14.21	17.37	0.82	-3.16
2003	7.04	12.31	11.58	1.06	0.74
2004***	11.74	9.83	15.06	0.65	-5.23
2005	14.26	21.09	16.93	1.25	4.16

2006**	21.12	21.81	22.01	0.99	-0.20
2007**	7.12	10.16	11.64	0.87	-1.48
2008**	17.28	20.07	19.16	1.05	0.91
2009**	14.06	17.17	16.78	1.02	0.39
2010**	11.22	11.84	14.67	0.81	-2.83
2011**	20.06	24.50	21.22	1.15	3.28
2012*	9.22	8.86	13.19	0.67	-4.33
2013	9.14	10.69	13.13	0.81	-2.45
2014	11.16	16.61	14.63	1.14	1.98
2015***	4.66	6.40	9.81	0.65	-3.41
2016	14.74	14.71	17.28	0.85	-2.57
2017	16.68	23.46	18.72	1.25	4.74
2018	7.40	10.29	11.84	0.87	-1.56
2019	18.44	21.64	20.02	1.08	1.62
2020	14.78	16.80	17.31	0.97	-0.51
Mean	12.69	16.33	15.76	**1.036**	**0.56**

* No seeding in target areas
** Seeding in Weber Basin only, not in Provo R Basin
*** Excluded from the mean due to excessive snow melt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.790698
R Square	0.625203
Adjusted R Square	0.607356
Standard Error	2.604868
Observations	23

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	6.361749	2.091542	3.041654	0.006201	2.012148
X Variable 1	0.741148	0.125223	5.918647	7.11E-06	0.480734

Western Uintas April 1 Snowpack, Multiple Linear Regression

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

Seeded period:

YEAR	Magic Mtn, ID	Badger Gulch, ID	Willow Flat, ID	Big Bend, NV	Strawberry Divide, UT	YOBS	YCALC	RATIO	EXCESS
1989	23.60	16.20	18.00	10.50	17.80	18.04	17.84	1.01	0.20
1990	10.20	7.70	4.00	0.00	12.80	14.79	13.45	1.10	1.34
1991	14.70	7.50	11.20	2.40	15.90	15.00	14.95	1.00	0.05
1992	3.60	3.00	3.70	0.00	6.90	10.29	9.05	1.14	1.24
1993	18.10	14.60	17.70	8.40	21.30	21.34	20.18	1.06	1.16
1994*	11.60	8.40	11.60	0.40	10.10	13.31	12.88	1.03	0.44
1995	15.70	10.40	12.90	3.90	16.90	18.43	16.52	1.12	1.91
1996*	21.20	14.70	16.30	10.20	22.40	22.21	19.96	1.11	2.25
2001	11.40	6.10	5.10	2.00	8.50	10.53	10.02	1.05	0.51
2002	20.90	15.80	14.30	10.40	12.90	14.21	14.88	0.96	-0.66
2003	10.60	4.20	8.10	2.00	10.30	12.31	10.71	1.15	1.61
2004***	20.20	13.00	11.40	3.60	10.50	9.83	13.30	0.74	-3.47
2005	16.70	9.80	14.90	7.70	22.20	21.09	18.68	1.13	2.40
2006**	28.20	18.20	21.00	14.50	23.70	21.81	21.03	1.04	0.78
2007**	14.00	5.20	6.00	1.80	8.60	10.16	9.51	1.07	0.65
2008**	20.00	16.80	19.00	11.60	19.00	20.07	19.16	1.05	0.91
2009**	20.40	10.20	15.50	10.10	14.10	17.17	13.50	1.27	3.67
2010**	15.70	11.20	10.80	8.40	10.00	11.84	11.97	0.99	-0.13
2011**	21.80	15.40	24.60	13.80	24.70	24.50	21.82	1.12	2.68
2012*	17.20	10.90	9.30	2.80	5.90	8.86	10.14	0.87	-1.29
2013	15.20	9.60	9.40	2.00	9.50	10.69	12.03	0.89	-1.34
2014	17.70	11.40	10.20	2.20	14.30	16.61	15.18	1.09	1.43
2015***	13.00	5.40	0.00	0.00	4.90	6.40	7.25	0.88	-0.85
2016	22.40	14.70	14.80	9.50	12.30	14.71	14.11	1.04	0.61
2017	19.80	15.10	15.20	10.10	23.20	23.46	20.64	1.14	2.82
2018	12.70	6.90	7.10	2.70	7.60	10.29	9.79	1.05	0.49
2019	21.20	17.70	19.00	10.40	23.90	21.64	22.32	0.97	-0.67
2020	21.40	15.60	13.00	8.40	15.50	16.80	16.37	1.03	0.43
Mean	17.22	11.45	12.85	6.64	15.30	16.33	15.38	**1.06**	**0.95**

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

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.90476
R Square	0.81859
Adjusted R Square	0.76523
Standard Error	2.01422
Observations	23

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	3.99574	1.84903	2.16099	0.04526	0.09463	7.89686	0.09463	7.89686
X Variable 1	-0.13065	0.21561	-0.6059	0.55256	-0.5855	0.32425	-0.5855	0.32425
X Variable 2	0.41099	0.30428	1.35067	0.19451	-0.231	1.05297	-0.231	1.05297
X Variable 3	0.11836	0.18066	0.65516	0.52114	-0.2628	0.49953	-0.2628	0.49953
X Variable 4	-0.17098	0.20373	-0.8392	0.41298	-0.6008	0.25886	-0.6008	0.25886
X Variable 5	0.55836	0.1195	4.67251	0.00022	0.30624	0.81048	0.30624	0.81048

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