Cloud Seeding Annual Report

Southern and Central Utah Program
2019-2020 Winter Season

Prepared For:

State of Utah Division of Water Resources

Utah Water Resources Development Corporation

Lower Colorado River Basin States

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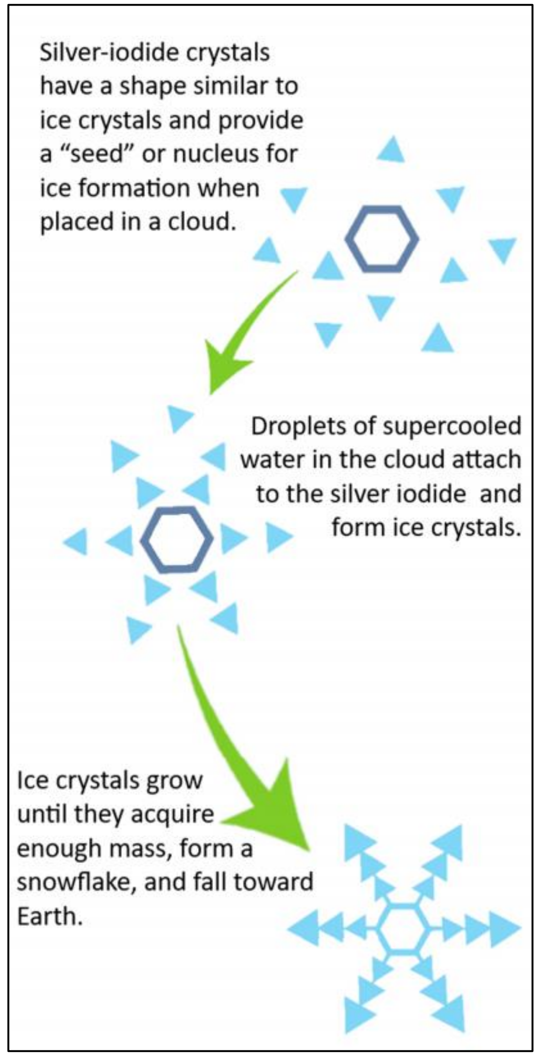
WEATHER MODIFICATION

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.

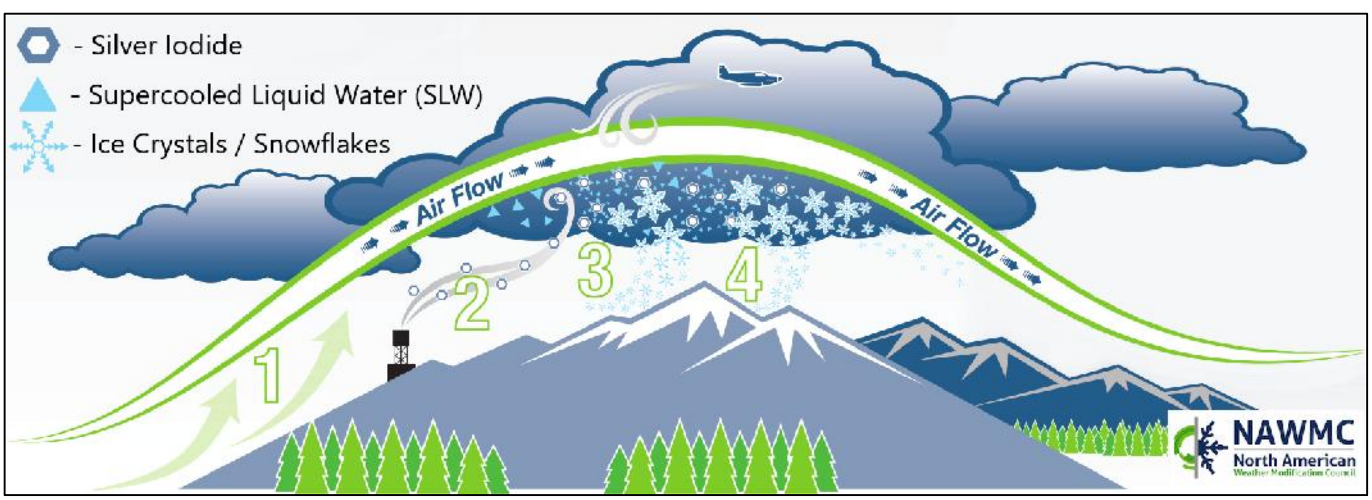


Safety

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

In many past winter seasons, cloud seeding has been conducted in several different regions within central and southern Utah. Since the mid-1970s seeding has been concentrated in the mountainous watersheds from Millard and Sanpete Counties southward to the Pine Valley Mountains and Washington County and the headwaters of the Sevier River in Iron and Garfield Counties. The mountainous portions of Tooele and Juab Counties have been included as seeding target areas since 1988. The intended target areas of this program generally include terrain above 7,000 feet elevation. The Southern and Central Utah Seeding Program utilizes approximately 70 ground-based, manually-operated (Cloud Nuclei Generator, or CNG) sites, containing a 2% silver iodide solution. The goal of the seeding program is to augment wintertime snowpack/precipitation over the seeded watersheds. Cost sharing for the seeding program is provided by the Utah Division of Water Resources, and additional funds from the Lower Colorado River Basin States has resulted in early-season (November 1st-15th) and late season (March 16th– April 15th) extensions to the seeding program since 2010.

Precipitation and snowfall were generally near normal during the 2019-2020 winter season, with the higher totals generally observed in far southern Utah. A total of 3,602.25 CNG hours were conducted during 18 storm periods for the core program this season, out of a maximum budgeted 6,500 hours. An additional 1,376.75 hours of seeding were conducted during 9 storm periods for the late-season Lower Basin Extension. 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 all seeded seasons combined. These evaluations utilize SNOTEL records collected by the Natural Resources Conservation Service (NRCS) at selected sites within and surrounding the seeded target area, as well as some seasonal streamflow data. Analyses of the effects of seeding on target area precipitation and snow water content have been conducted for this seeding program, utilizing target/control comparison techniques. Evaluation of December – March precipitation data have suggested long-term seasonal increases averaging 12% for both Eastern Tooele County and the primary target areas of central and southern Utah. April 1st snowpack evaluations have suggested 10% increase in Eastern Tooele County and 4% increases for the central and southern Utah watersheds. As discussed in section 6.0 of the report, the precipitation evaluation results are stronger mathematically, and suggest roughly a 1.3” increase in seasonal precipitation in the target areas due to seeding. This would likely produce an average additional runoff of more than 70,000 acre-feet annually in these watersheds.

1.0 INTRODUCTION

Since the mid-1970s, operational cloud seeding has been routinely conducted throughout the winter and early spring seasons over many of the mountainous watersheds of central and southern Utah. Water managers and others concerned about maintaining adequate water supplies have recognized that application of cloud seeding technology can be a viable method available to augment and help stabilize water supplies. By employing cloud seeding it could be possible to moderately increase the amount of precipitation and runoff beyond that which would have occurred naturally. Operations can be suspended in portions of or all of certain winter seasons that experience excessive amounts of precipitation. Cloud seeding suspensions, for example, were invoked in the 1982, 1983, 1993, 1995, 2005, 2008, 2010, 2011, 2017 and 2019 water years. Operations were suspended entirely in the 1984 water year due to abnormally wet conditions.

In a number of past winter seasons, cloud seeding has been conducted in many different regions within central and southern Utah. Since the mid-1970s seeding has been concentrated in the mountainous watersheds from Millard and Sanpete Counties southward to the Pine Valley Mountains and Washington County and the headwaters of the Sevier River in Iron and Garfield Counties. The mountainous portions of Tooele and Juab Counties have been included as seeding target areas since 1988. A map showing the current boundaries of these seeded target areas is provided in Figure 1.1. The target areas, generally terrain above 7,000 feet MSL, were selected as high-yield areas with substantial snowpack accumulation. These areas are the primary contributors to spring and summer streamflow. Figure 1.2 depicts the average annual precipitation for the State of Utah. This figure graphically demonstrates these higher-yield areas.

Traditionally, the sponsoring counties or water conservancy districts have contracted the cloud seeding program in central and southern Utah with the Utah Water Resources Development Corporation (UWRDC). The UWRDC, a non-profit organization, was formed in the 1950s to act as a liaison between the agencies desiring cloud seeding and the company providing the actual cloud seeding equipment and operations. North American Weather Consultants (NAWC), has been contracting with the UWRDC in this capacity. During the current water year, the State of Utah, through the Division of Water Resources, was again a co-sponsor of this program through 50% cost sharing.

Cloud seeding in Utah is regulated by the Utah Department of Natural Resources through the Division of Water Resources. Utah law requires that operators conducting cloud seeding have both a license and a site-specific permit for the area(s) to be seeded. The three Lower Colorado River Basin States (Arizona, California and Nevada), as in previous seasons, provided additional funding to extend the operational period in those areas of the southern target area, which contain tributaries to the Colorado River.

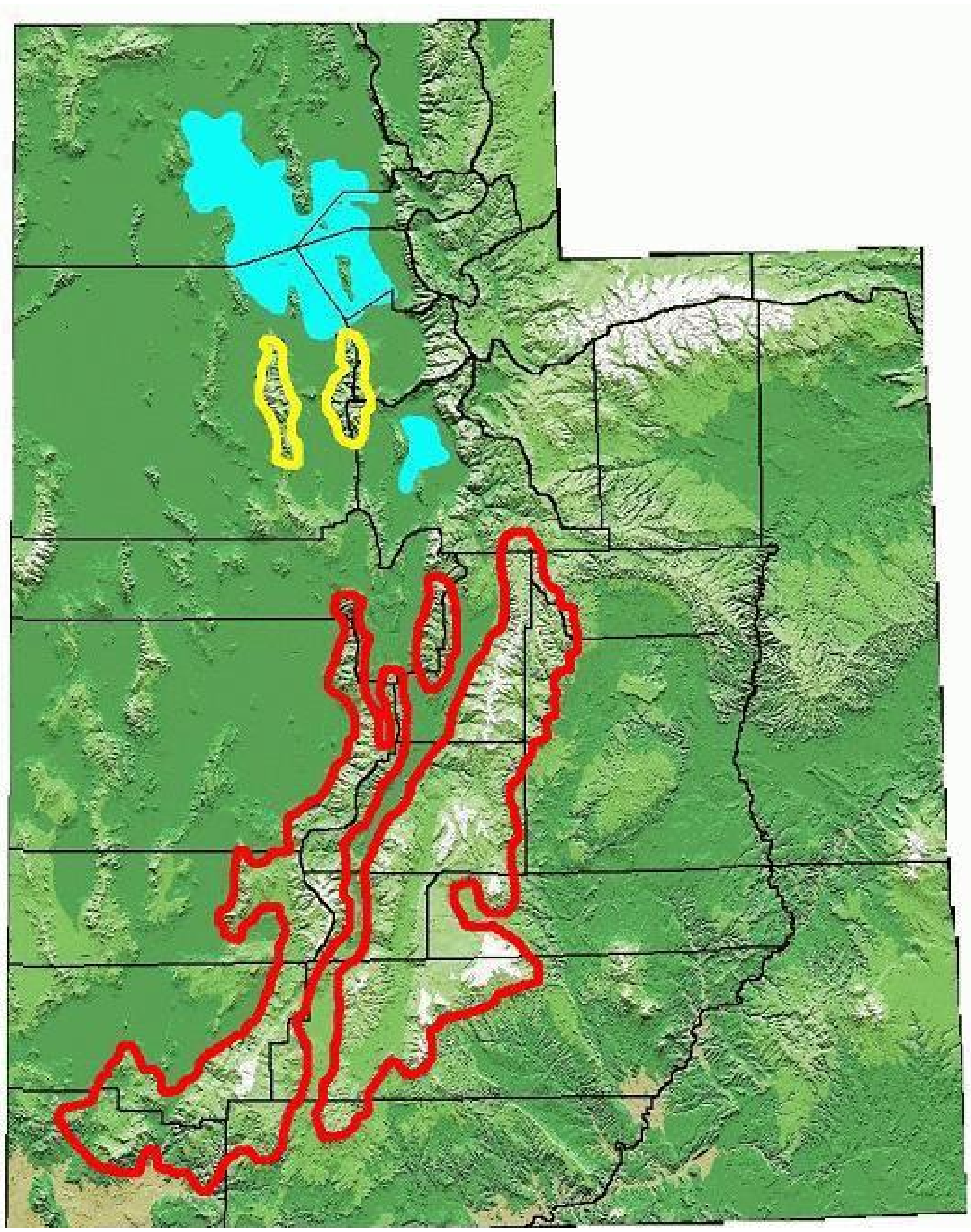

Figure 1.1 Seeded target areas in central and southwestern Utah; Eastern Tooele Target (yellow) and Primary Target (red)

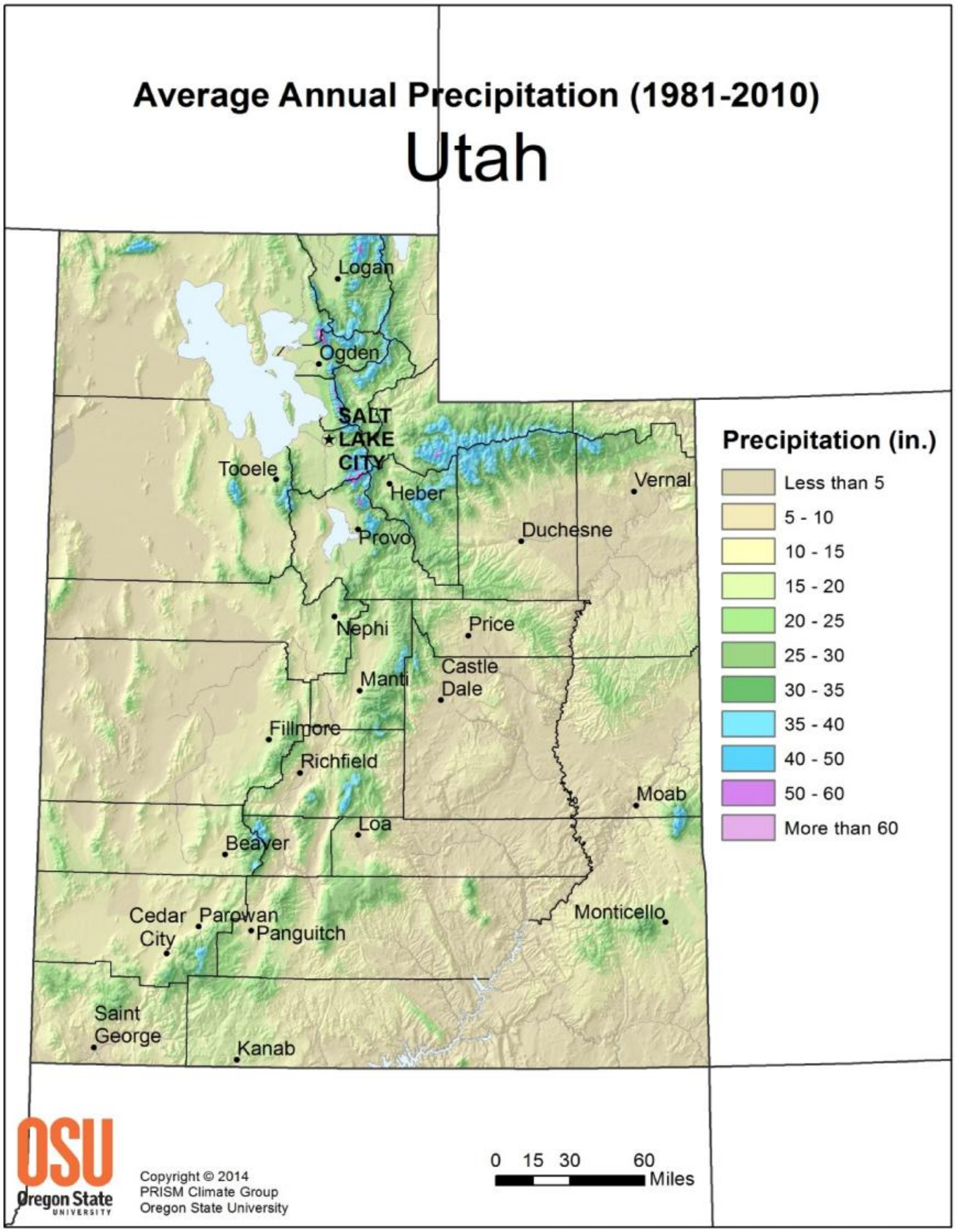

Figure 1.2 Utah average annual precipitation

1.1 Core Program and Extension Periods

As the demand for fresh water continues to grow in the southwest, the Colorado River is an extremely important component of the surface water supply in the region. Various Colorado River water interests (e.g. the Lower Basin States) have worked together in recent years to develop new or improved strategies aimed at enhancing the flow of the river better managing the water resources. One of the most promising strategies is increasing the use of cloud seeding for precipitation augmentation where and when viable seeding opportunities occur.

The primary Central and Southern Utah Seeding Program, funded by various Utah water interests and the Division of Water Resources, was active from November 16 – April 15 this season. The Central/Southern Utah Project was one of two Utah projects selected to receive supplemental Lower Basin funding. Via an agreement between the Lower Basin States and Utah's Division of Water Resources, supplemental funds for extension of the operational seeding period for a portion of the Central/Southern Project have been provided. The extension periods funded by Lower Basin States were from November 1-15 and March 16 – April 15 during the 2019-2020 winter season. Thus, additional benefit was realized by some of the Utah sponsors at no additional cost to them.

1.2 Installation and Operation of Icing Rate Meters

An earlier agreement with the three Lower Basin States provided funds to purchase some hardware for three remote icing rate meters. The Lower Basin States provided funds in the 2009 agreement to install and operate two of these sites beginning during the 2009-2010 winter season. One site was installed in central Utah in conjunction with a Utah Department of Transportation site (Skyline), a second site was established at the Brian Head ski area in southern Utah. Beginning with the 2012-13 winter season, a third icing meter site has been active at Dry Ridge in the Uintas (this is within the High Uintas seeding program target area). The icing rate meters detect the presence of supercooled liquid water (SLW) cloud droplets embedded in naturally occurring winter storms. These droplets are the target of the cloud seeding operations. Funds from the Lower Basin States are also provided for the analysis of the ice detector data to improve understanding of when/where SLW occurs in cold-season storm events. A separate report will once again cover the analyses of data collected from these sites during this past season.

2.0 PROJECT DESIGN

2.1 Background

Evaluations of this long-standing operational seeding project have consistently indicated increases in wintertime precipitation during the periods in which cloud seeding was conducted. Statistical analyses have suggested seasonal increases in precipitation that may be attributed to the cloud seeding program, averaging between 5% and 15% (Griffith et al., 2009). Operational procedures during the 2019-2020 Central/Southern Utah cloud seeding program utilized the basic principles of applying cloud seeding technology that have been shown to be effective during more than 40 years of wintertime cloud seeding for the mountainous regions of Utah. Continued increases in availability of weather data and forecast products have led to improved seeding opportunity recognition capabilities, and continued analysis of the effectiveness of operational cloud seeding projects is leading to improved confidence in the accuracy of the long-term average effects of the Central/Southern Utah Program. NAWC has incorporated observational, seeding method and evaluation enhancements into the project when they are believed to be of practical value to the project.

2.2 Seedability Criteria

Project operations have utilized a selective seeding approach, which has proven to be the most efficient method, providing the most cost-effective results. Selective seeding means that operations are conducted only during storms (or portions of storms) when seeding is likely to be effective. These decisions are based on several criteria, which determine the seedability of the storm. The criteria deal with meteorological characteristics (temperature, stability, wind flow and moisture content) associated with winter cloud systems. Table 2-1 provides the seeding criteria which NAWC has established for the southern/central Utah winter cloud seeding program.

Seeding cannot be effective unless the seeding material reaches portions of clouds equal to or colder than the warmest activation temperature (near -5°C) for silver iodide. This will generally be accomplished if the cloud base is at a lower elevation than the mountain crest and no temperature inversions or stable layers exist between the elevation of the cloud seeding generator and the cloud base. There were some storm events during the season where the cloud temperatures were too warm for seeding to be effective according to NAWC's operational criteria (see Table 2-1, item 4) and were therefore not seeded. The existence of low-level stability can inhibit the effects of seeding by trapping silver iodide particles released from ground-based sources and preventing them from traveling to portions of the cloud where they can aid in nucleation and eventual precipitation production. Griffith et al., (2013) provides additional information on the seedability of winter storms.

Table 2-1
NAWC Winter Cloud Seeding Criteria

1)	CLOUD BASES ARE BELOW THE MOUNTAIN BARRIER CREST.
2)	LOW-LEVEL WIND DIRECTIONS AND SPEEDS 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).

2.3 Equipment and Project Set-Up

During the autumn of 2019, following a period of off-season maintenance, NAWC technicians re-installed the ground-based cloud seeding generators at sites selected to produce seeding plumes over the target areas in various wind situations. The target areas are discussed in more detail in Section 4.0. The seeding generator site locations, approximately 70 in all, are shown in Figure 2.1. Information on these locations is provided in Table 2-2.

Eleven ground-based seeding sites were available in eastern Tooele County (ET) during the season, located throughout the Tooele Valley from Erda and Grantsville southward to Faust, with additional sites to the west of the Stansbury Range, in Skull Valley. These locations allow for targeting of this portion of the seeding target area (Oquirrh and Stansbury Mountains) during a variety of wind flow situations.

The second seeded target group is referred to as the Primary Target (PT). This target area covers a large portion of central and southwestern Utah, including the principle mountain ranges listed below.

- Wasatch Range - northeast of Nephi
- Wasatch Plateau - east of Mt. Pleasant to east of Manti
- San Pitch Mountains - east of Levan to Gunnison
- Fish Lake Hightop Plateau - east of Koosharem
- Pavant Range - east of Fillmore to Cove Fort
- Tushar Mountains - east of Beaver
- Sevier Plateau - east of Salina to Panguitch
- Valley Mountains - east of Scipio
- Paunsaugunt Plateau - east of Panguitch and Hatch
- Markagunt Plateau - east of Paragonah to Brian Head
- Pine Valley/Harmony Mountains - southwest of Cedar City to St. George
- Kolob Terrace - south of Cedar City to Springdale

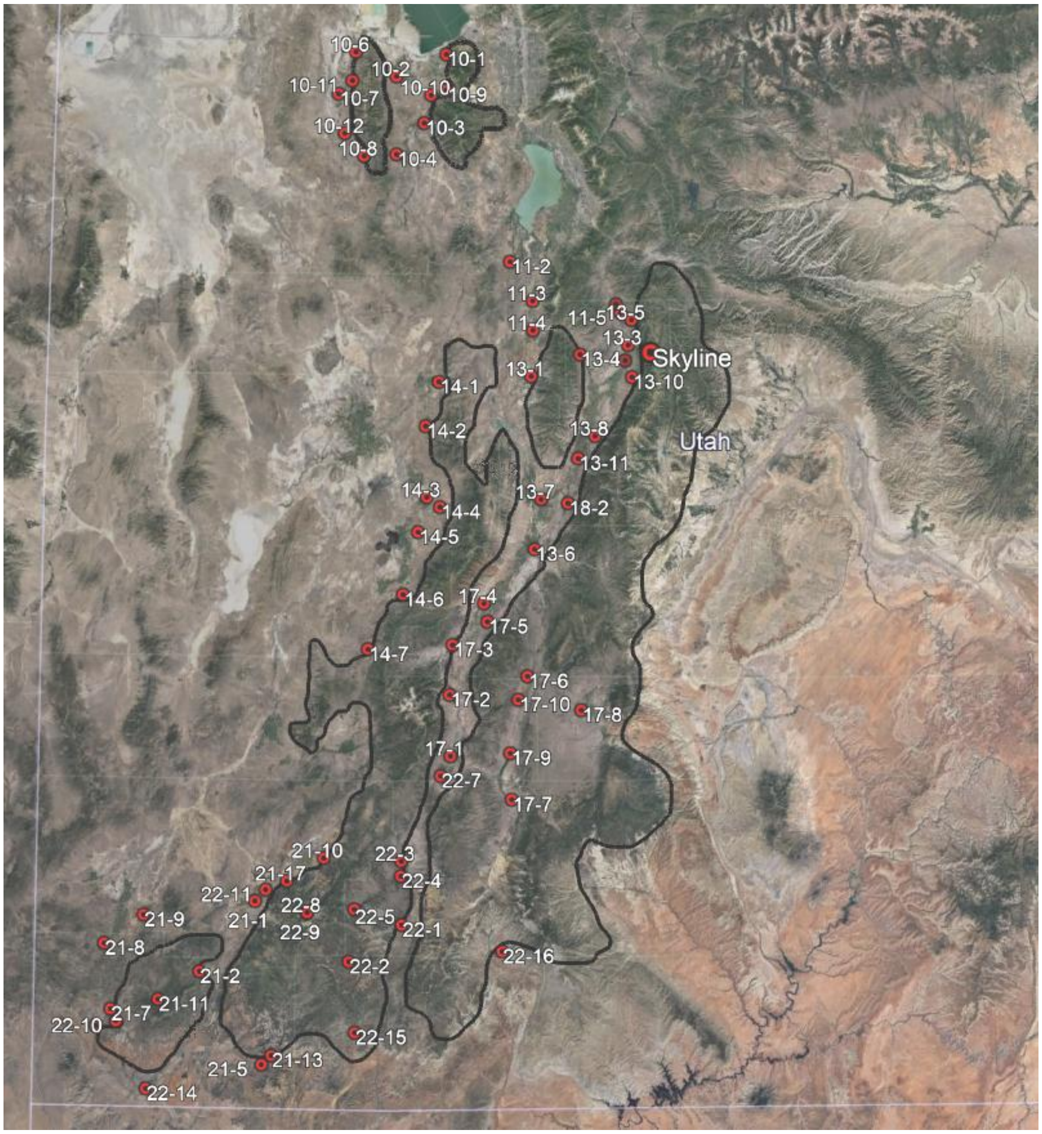

Figure 2.1 Target areas and seeding site locations (not all sites may be seen on map due to proximity to others)

Table 2-2
Seeding Site Locations

Site Number	Name	Lat. (N)	Long. (W)	Elevation (feet)
10-1	Lakepoint	40°40.65’	112°15.22’	4430
10-2	Grantsville	40°35.99'	112°28.88'	4342
10-3	Stockton	40°26.12'	112°21.18'	5234
10-4	Clover	40°19.50'	112°28.75'	5342
10-6	Skull Valley North	40°41.11'	112°40.10'	4289
10-7	Skull Valley Central	40°32.20'	112°44.74'	4390
10-8	Terra	40°19.12'	112°37.60'	5166
10-9	Pine Canyon	40°33.09'	112°15.15'	5095
10-10	Settlement Canyon	40°31.14’	112°18.16’	5140
10-11	Skull Valley #3	40°35.00’	112°41.00’	4300
10-12	Skull Valley #4	40°23.87’	112°42.92’	4890
11-1	Indianola	39°48.20'	111°29.07'	5986
11-2	Elberta	39°57.12'	111°57.72'	4732
11-3	Mona	39°48.93’	111°51.61’	4943
11-4	Nephi West	39°42.78'	111°51.56'	5042
11-5	Hideaway Valley	39°46.32'	111°27.90'	6300
13-1	Levan	39°33.17'	111°52.06'	5286
13-3	Fairview	39°39.61’	111°25.87’	6125
13-4	Fountain Green	39°37.69'	111°38.88'	5985
13-5	Milburn	39°44.88'	111°24.96'	6787
13-6	Salina	38°57.22'	111°51.21'	5190
13-7	Centerfield	39°07.60'	111°49.43'	5100
13-8	Ephraim	39°20.73'	111°34.95'	5626

Site Number	Name	Lat. (N)	Long. (W)	Elevation (feet)
13-10	Mt. Pleasant	39°32.46'	111°27.03'	5981
13-11	Manti	39°16.08'	111°39.51'	5505
13-12	Fairview South	39°36.44'	111°26.71	5855
14-1	Leamington	39°31.99'	112°16.92'	4721
14-2	Oak City	39°22.76'	112°20.43'	5059
14-3	McCornick	39°07.95'	112°20.01'	4848
14-4	Holden	39°05.92'	112°16.49'	5077
14-5	Fillmore	39°00.71’	112°22.30’	4879
14-6	Kanosh	38°47.71'	112°26.20'	5048
14-7	Cove Fort	38°36.35'	112°35.44'	5942
17-1	Junction	38°14.28'	112°13.42'	6018
17-2	Marysvale	38°26.98'	112°13.72'	5870
17-3	Joseph	38°37.34'	112°13.00'	5435
17-4	Richfield	38°45.96’	112°04.68’	5296
17-5	Annabella	38°42.17'	112°03.77'	5316
17-6	Koosharem	38°30.87'	111°53.13'	6973
17-7	Antimony	38°05.29'	111°57.25'	6661
17-8	Loa	38°23.83'	111°38.89'	7052
17-9	Angle	38°14.91'	111°57.65'	6415
17-10	Greenwich	38°26.00’	111°55.54’	6882
18-2	Mayfield	39°06.97'	111°42.52'	5550
21-1	Cedar City West	37°43.84'	113°04.53'	5525
21-2	New Harmony	37°29.05'	113°18.85'	5355
21-5	Rockville	37°09.70'	113°02.35'	3737
21-7	Veyo	37°20.79'	113°42.04'	4544

Site Number	Name	Lat. (N)	Long. (W)	Elevation (feet)
21-8	Enterprise	37°34.50'	113°43.99'	5345
21-9	Newcastle	37°40.61'	113°33.73'	5242
21-10	Paragonah	37°52.98’	112°46.56’	5880
21-11	Pine Valley	37°23.05'	113°29.57'	6579
21-12	Gunlock	37°17.16'	113°45.88'	3638
21-13	Springdale	37°11.65'	112°59.83'	3987
21-17	Summit	37°48.04'	112°55.96'	6009
22-1	Hatch	37°39.20'	112°26.00'	6922
22-2	Duck Creek	37°31.50’	112°39.80’	8451
22-3	Spry	37°52.43'	112°26.24'	6564
22-4	Panguitch	37°49.33'	112°26.30'	6619
22-5	Panguitch Lake	37°42.39’	112°38.47’	8255
22-7	Circleville	38°10.27'	112°16.03'	6082
22-8	Brian Head Summit	37°41.64'	112°50.76'	9591
22-9	Brian Head	37°41.58'	112°51.00'	9700
22-10	Dammeron Valley	37°18.26'	113°40.56'	4546
22-11	Enoch	37°46.44'	113°01.55'	5566
22-14	St. George	37°04.16'	113°32.56'	2709
22-15	Orderville	37°16.62’	112°38.10’	5470
22-16	Henrieville	37°33.72’	112°59.64’	6000

The primary target area reaches from eastern Juab County in central Utah, southward to the northern portions of Washington and Kane Counties in southwestern Utah.

There are approximately 60 seeding generator sites available for the primary target areas. These generators extended roughly in north to south lines west of the target areas in eastern Juab and Millard well as throughout Sanpete, Sevier and Piute Counties. Further south, generators were located in Iron, Garfield, Kane, and Washington Counties. This equipment array provides various seeding options regardless of wind direction, as some generators are nearly always upwind of a portion of the target area during storms. It should be noted that winds during winter storms in Utah typically blow from the west toward the east, most commonly from the southwest before frontal passages and from the northwest following cold frontal passages.

The cloud seeding equipment at each site includes a cloud seeding generator unit and a propane gas supply tank. The seeding solution consists of two percent (by weight) silver iodide (AgI), complexed with small portions of sodium iodide and para-dichlorobenzene, in solution with acetone. This particular solution is used because it is formulated specifically to be a "fast-acting" nucleation agent via the condensation-freezing mechanism, rather than via the slower contact nucleation mechanism. This is an important characteristic, given the relatively narrow mountain barriers within the cloud seeding target areas in Utah. The 2% silver iodide solution has been used throughout most of the history of the program.

The seeding units are manually operated by a local operator igniting propane in a burn chamber, and then adjusting the flow of the seeding solution into the burn chamber through a flow rate meter. The propane gas pressurizes the solution tank, which allows the solution to be forced into the burn chamber. The regulated seeding solution is sprayed into the propane flame, where microscopic silver iodide crystals are formed through the combustion process. The silver iodide is released at a rate of eight grams per hour, and after combustion it produces these ice-forming nuclei crystals, which closely resemble natural ice crystals in structure. These crystals become active as ice-forming nuclei beginning at temperatures near -5°C (23°F) in-cloud. Since experience has indicated that seeding is most effective within a particular temperature range (Griffith et al., 2013), the seeding generators were operated only during those periods when the temperatures within the cloud mass were between about -5 and -25°C (+23 to –13°F). For the seeding to be effective, the AgI crystals must become active in the cloud region which contains supercooled liquid water droplets sufficiently far upwind of the mountain crest so that the available supercooled liquid water can be effectively converted to ice crystals which will then grow to snowflake sizes and fall out of the cloud onto the mountain barrier. If the AgI crystals take too long to become active, or if the temperature upwind of the crest is too warm, the plume will pass from the generator through the precipitation formation zone and over the mountain crest without freezing the cloud drops in time to affect precipitation in the desired area.

Most storms that affect Utah's mountains are associated with synoptic (large-scale) weather systems that move into Utah from the southwest, west, or northwest. Usually they consist of a frontal system and/or an upper trough, with the air preceding the front or trough flowing from the south or southwest. As the front/trough passes through the area, the wind flow changes to the west, northwest, or north and the atmosphere cools. Clouds and precipitation may precede the front/trough passage, or they may mostly occur along the boundary of the colder air mass that moves into the region, and in some cases, continuing in the airmass behind the front or trough. For that reason, the seeding generators were situated to enable effective targeting in varying wind flow regimes, primarily ranging from southwesterly to northwesterly. Winds in meteorology are reported from the direction with which the winds are blowing. For example, a southwest wind means the winds are blowing towards the northeast.

The core 2019-2020 cloud seeding program for central and southern Utah began on November 15, 2019 and ended on March 15, 2020. Time extensions, funded by the Lower Basin States, covered the periods of November 1-15, 2019 and March 16 – April 15, 2020 for the portions of the target area that potentially contribute runoff to the Colorado River. The seeding generators located in the central valley from approximately Milburn to Hatch were used in this program extension, as well as a few sites in the area near Koosharem, Antimony, and Loa, plus those in the vicinity of Brian Head and the Pine Valley Mountains. Seeding from the central valley sites would be expected to produce positive seeding effects on both the western and eastern slopes of the Wasatch Plateau. The eastern slopes of the Wasatch Plateau are tributary to the Colorado River. Seeding from these sites and those near Antimony would provide increases in precipitation on the western and eastern slopes of the Escalante Mountains (eastern slopes tributary to the Colorado River) and the Thousand Lakes and Boulder Mountains (also tributary to the Colorado River). Figure 2.2 is a map of the areas that contribute runoff to the Colorado River, areas where early and late-season time extensions to the seeding program were funded by the Lower Basin States. These areas are also included as part of the core program and so are subject to seeding operations during the entire seasonal period.

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

2.4 Suspension Criteria

NAWC has a standing policy of operating within guidelines adopted to ensure public safety. Accordingly, NAWC, working in conjunction with the Utah Division of Water Resources, has developed criteria and procedures for the suspension of cloud seeding operations (detailed in Appendix A). Due to a large number of wildfires during the past couple of years, NAWC's suspension criteria included situations that might impact several burn areas located with the central/southern Utah target areas during periods that might be conducive to debris flows. There were no seeding suspensions during the 2019-2020 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 sources, including some subscriber services. This information includes weather forecast model data, surface observations, rawinsonde (weather balloon) upper-air observations, satellite images, NEXRAD radar information, and local webcams. This information helps NAWC meteorologists to determine when conditions are appropriate for cloud seeding. Each of NAWC's meteorologists also has a fully capable computer system with internet access at home, to allow 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.

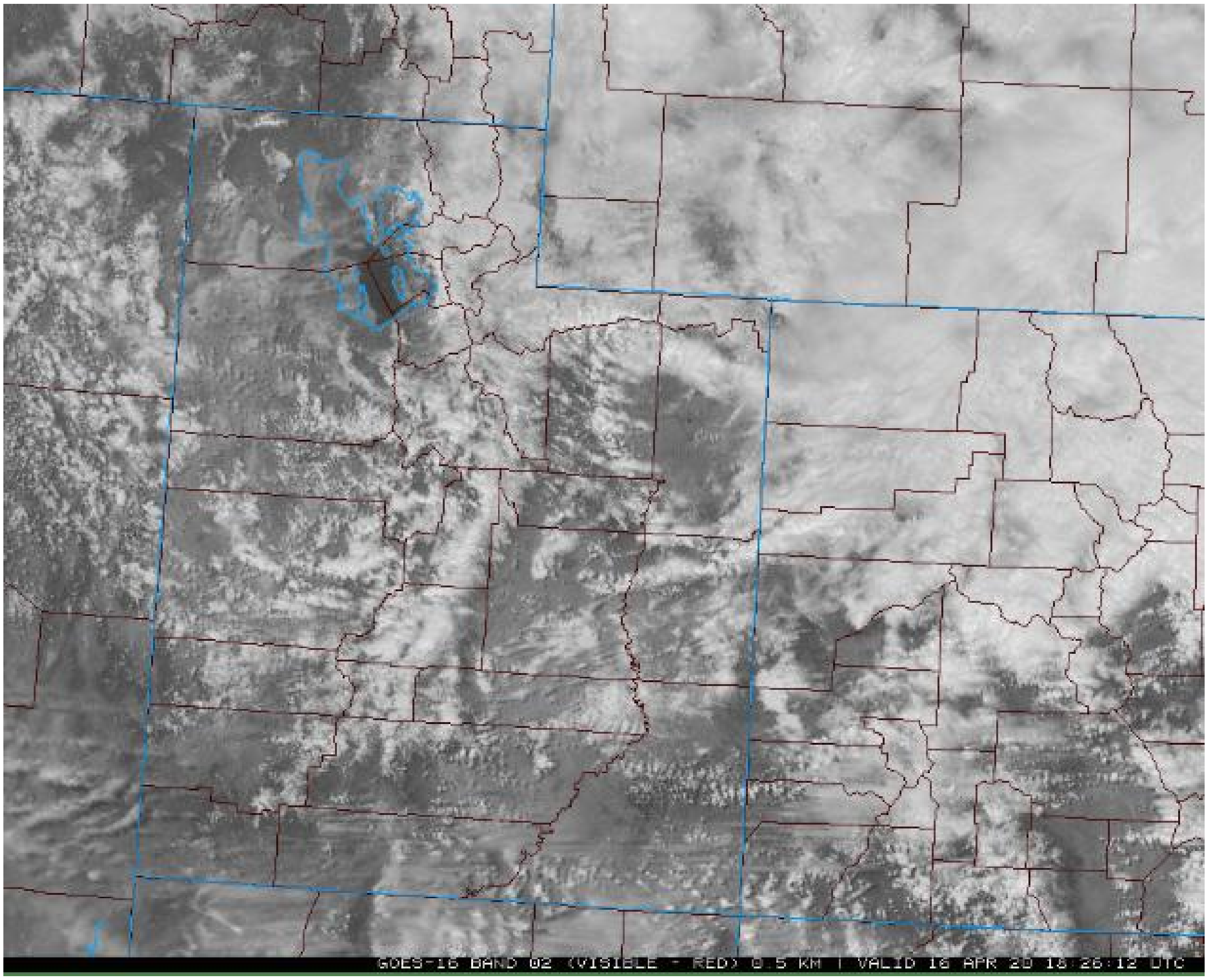

Figure 3.1 **Visible spectrum satellite image at 1226 MDT April 16 as a trough pushed through the state**

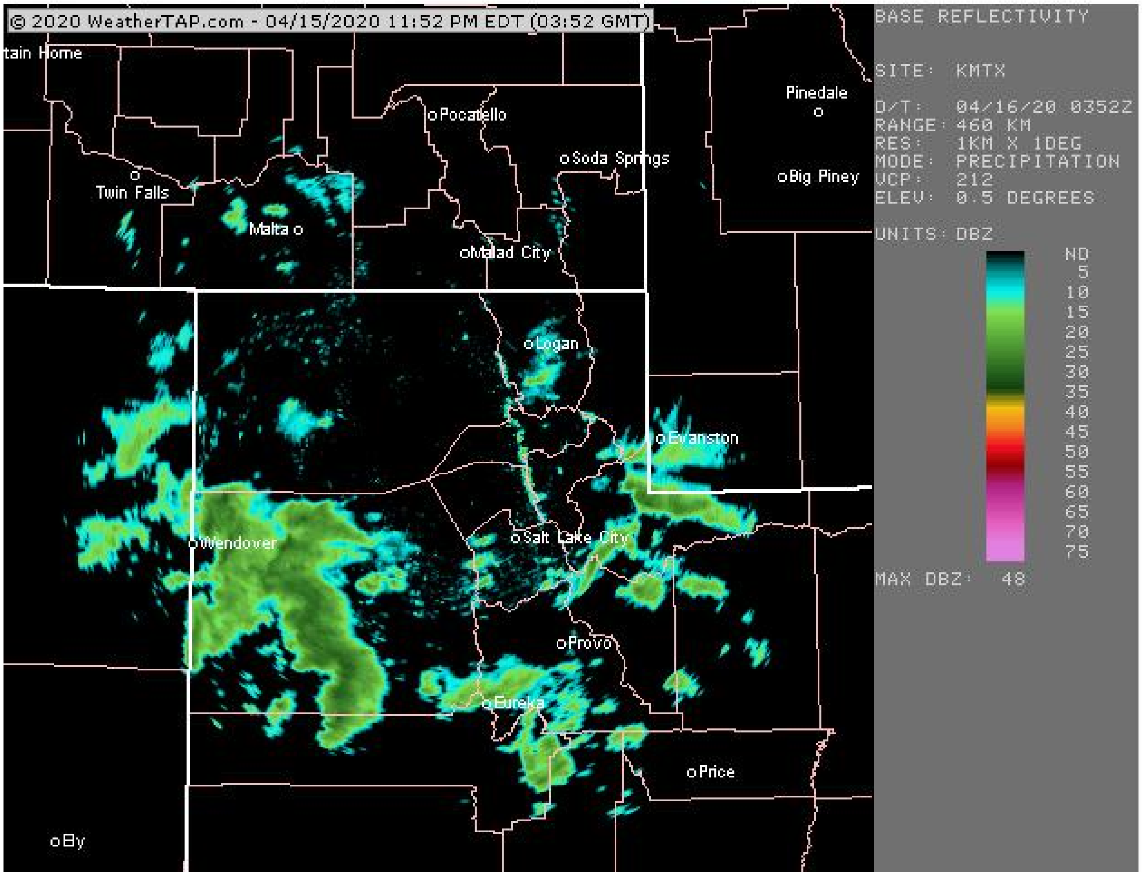

Figure 3.2 Weather radar image of northern and central Utah on April 15, 2020

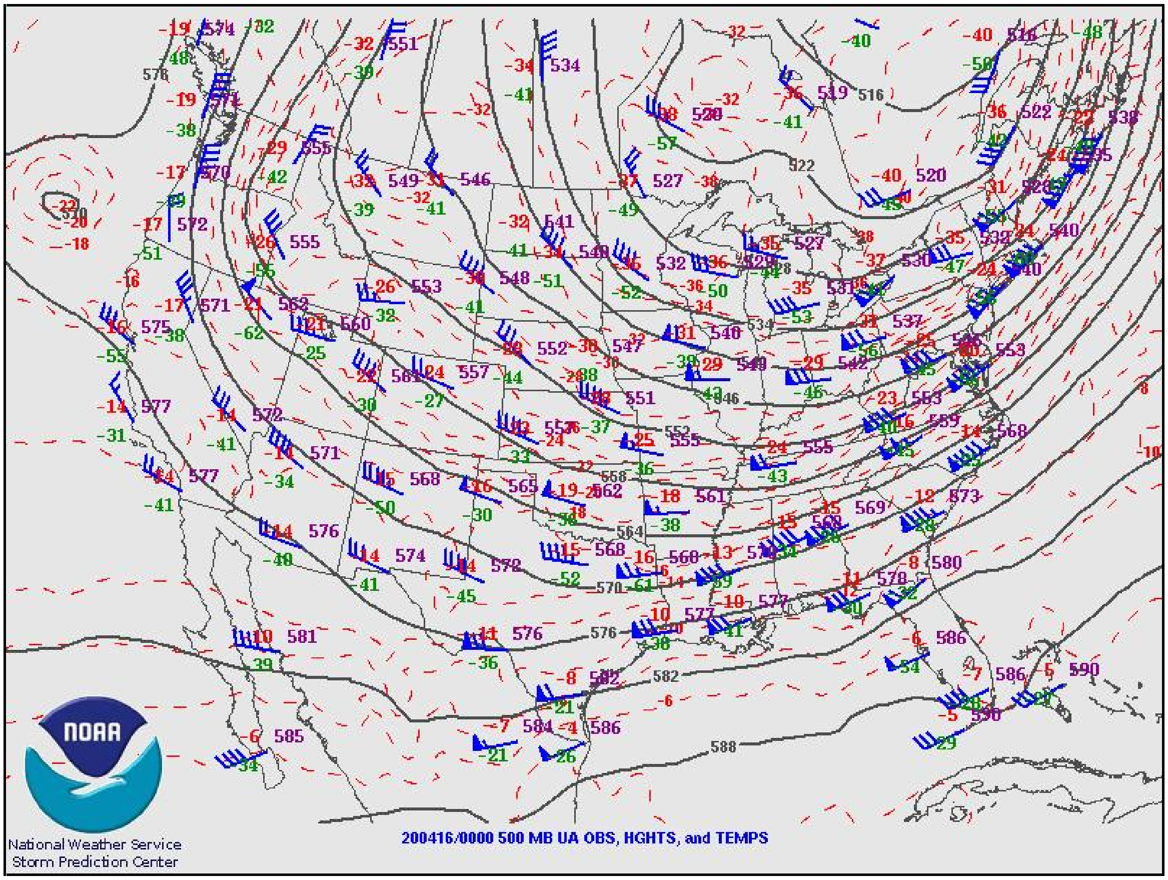

Figure 3.3 500 mb map at 1800 MDT on April 15, 2020, showing a trough covering much of the U.S.

Global and regional forecast models are an important tool for operational cloud seeding decisions. 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 Figure 3.4.

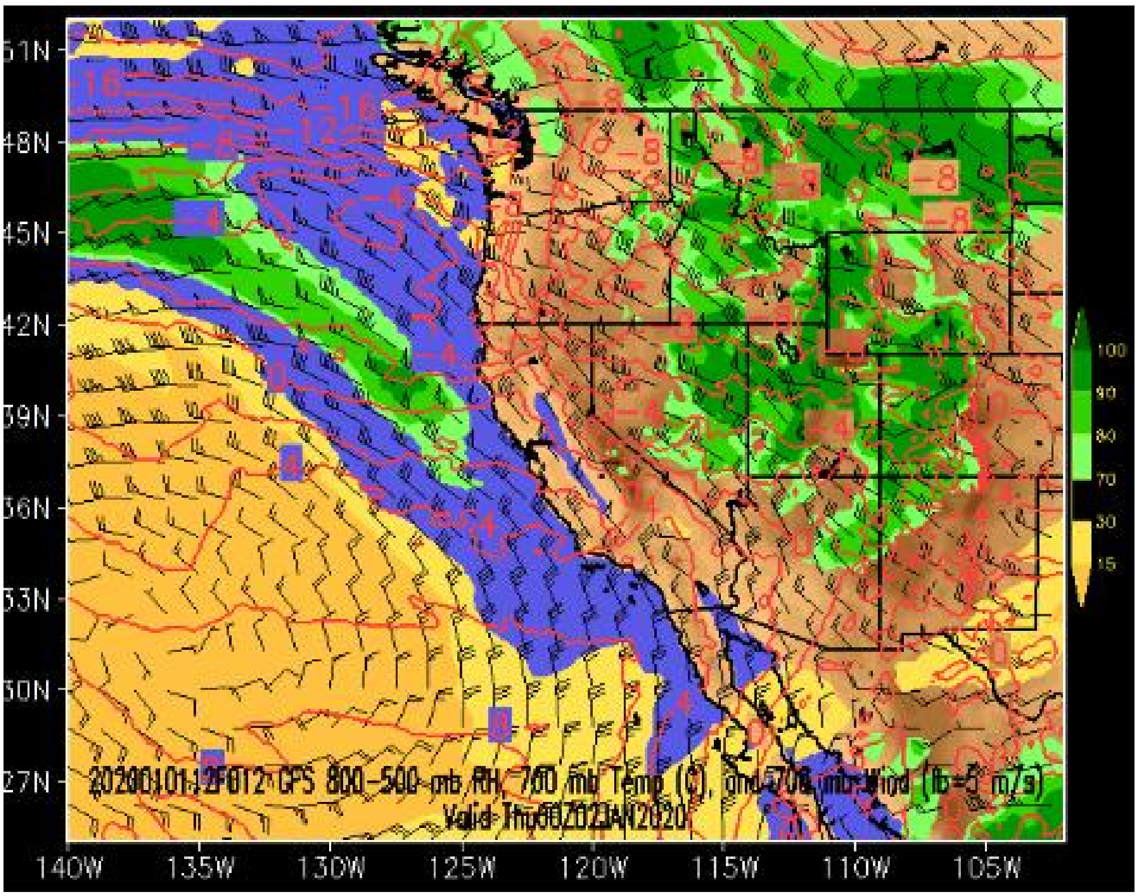

Figure 3.4 GFS model forecast (700-mb wind/moisture/temperature panel) during a storm event on January 1, 2020.

Figure 3.5 provides predictions of ground-based seeding plume dispersion for a storm period in central and southern Utah using the National Oceanic and Atmospheric Administration's HYSPLIT model (information provided in Appendix B). This model assists in estimating the horizontal and vertical spread of a plume from potential ground-based seeding sites in real-time, based on wind fields contained in the weather forecast models.

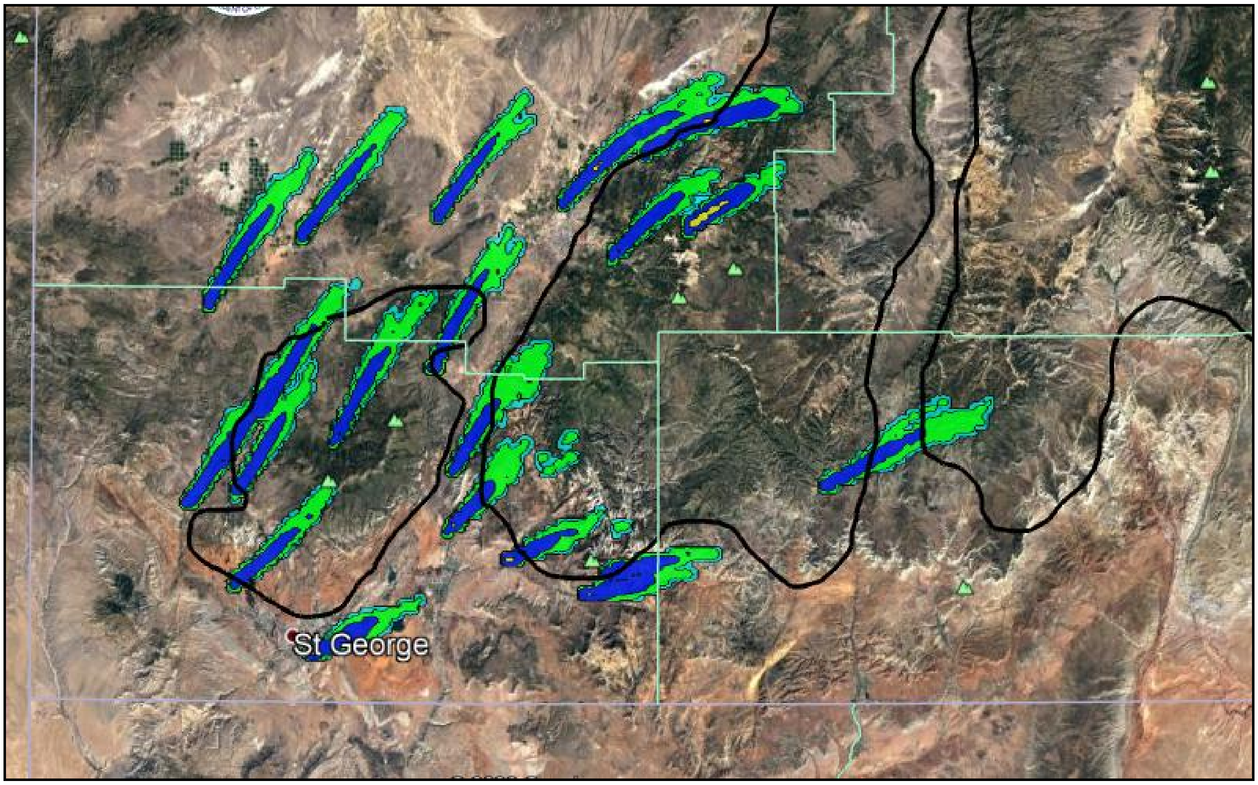

Figure 3.5 HYSPLIT plume dispersion forecast from a seeding storm event on the March 20, 2020, for a portion of the target area in far southwestern Utah (black outlines). This shows short term (1-hour) plume dispersion forecasts for potential seeding sites.

An agreement between the three Lower Colorado River Basin States and the Utah Division of Water Resources has provided funding to acquire and install icing rate meters and special precipitation detectors at three sites in Utah. These sites were re-established for the 2019-2020 winter season, with two of them located in the Central/Southern Utah project area. The two in the project area were located at Brian Head (east of Cedar City) and at Skyline (east of Fairview). The ice detectors are used to measure the occurrence of supercooled liquid cloud droplets, useful in making real-time seeding decisions, as well as for later analysis. The icing meter cycles when a certain amount of icing accumulates on a small probe. The probe is then heated briefly to de-ice the probe. Multiple cycles are indicative of likely favorable seeding situations, assuming that the other seeding criteria (especially temperature) are met. Figure 3.6 provides a photograph of an installation at Brian Head. Figure 3.7 provides a close-up of this suite with labels assigned to the various components, with a similar site located at Skyline (east of Fairview in central Utah).

Figure 3.6 Special instrument suite at Brian Head Ski Area

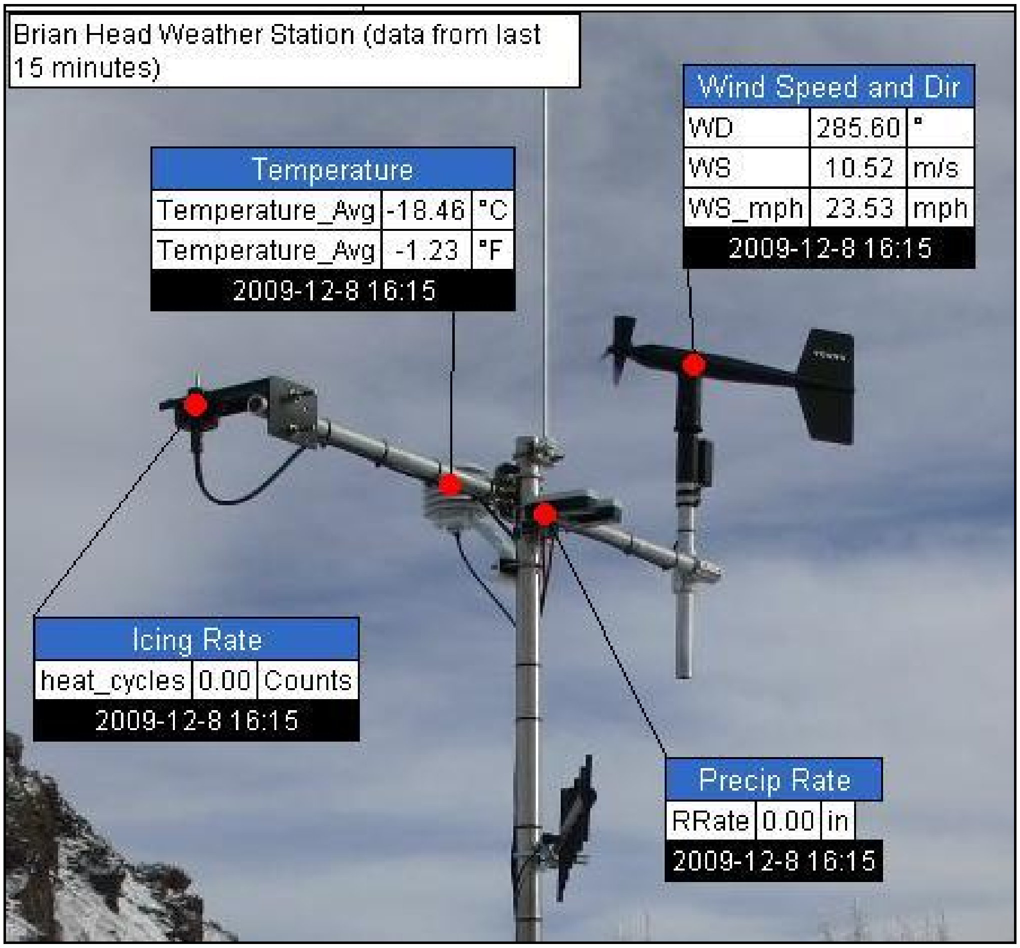

Figure 3.7 Close-up photo of the special instrument suite at Brian Head

During the 2019-2020 season, a passive microwave radiometer was sited at Brian Head, which was made possible with funding by the Lower Colorado River Basin States. This was considered an excellent location, based on the meteorology of this area and importance to runoff contributing to the Colorado River. NAWC has also worked with Brian Head personnel for a number of years in support of the icing meter site located there. The radiometer provides a vertical profile of various atmospheric parameters, particularly the occurrence of liquid water along with associated temperature profiles. This allows for identification of areas of SLW at suitably cold temperatures, as well as indications of the temperature profile of the lower atmosphere which affects the dispersion of seeding material. These observations are useful both operationally in real-time and for post-analysis. The location of this radiometer was near the icing meter site also located at Brian Head, with a scan angle toward the icing meter site deliberately selected. This will provide a useful comparison of data from the two instruments. An analysis of the radiometer data from Brian Head will be included in a separate report. Figure 3.8 is an image of the Brian Head radiometer, and Figure 3.9 is an example of radiometer data.

Figure 3.8 Radiometer sited at the Brian Head Ski Resort in Brian Head, Utah

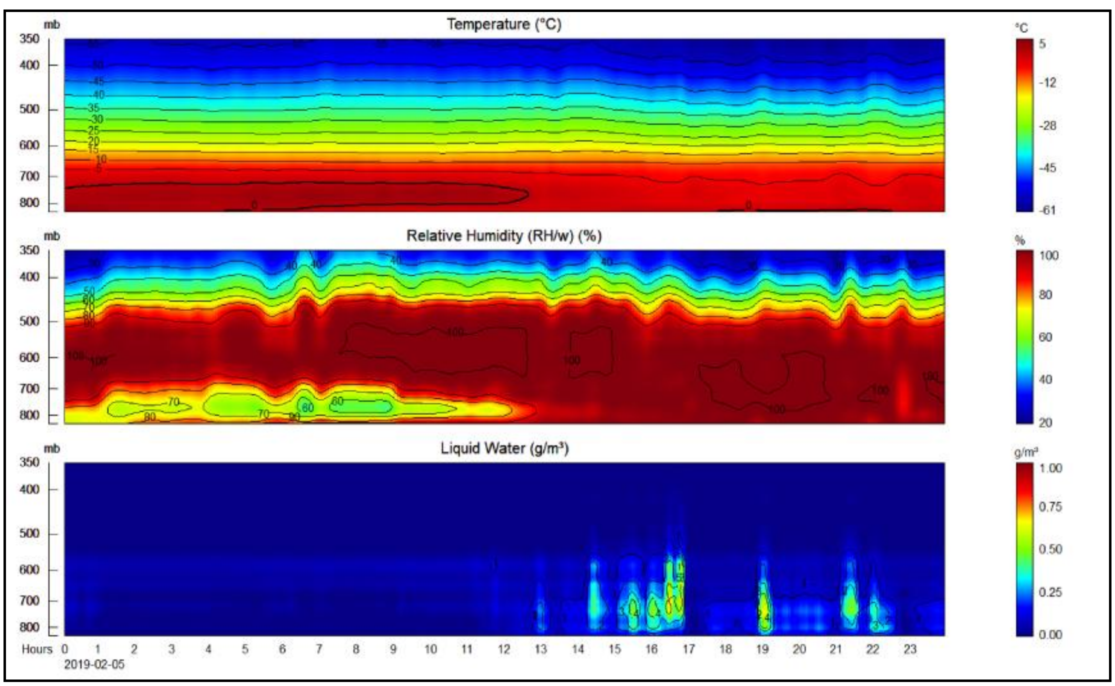

Figure 3.9 Example of radiometer data

4.0 OPERATIONS

A total of 18 storm events were seeded during the core program contract period (November 15th – March 15th), and nine additional events were seeded during the spring extension period (March 16th – April 15th). There were no seeding opportunities during the November 1-15 portion of the Lower Basin States extension this season. In all, there were three storm events seeded in November, four events in December, seven in January, two in February, eight in March, and three in April. For the regular contract period, a cumulative 3,602.25 generator hours were utilized. For the Lower Basin extension, there was an additional 1,376.75 generator hours of seeding conducted. Figure 4.1 shows cumulative seeding hours for the core program this season. Table 4-1 shows the dates and number of CNGs used for each of the storm events, and Appendix B shows detailed usage for the individual CNG sites.

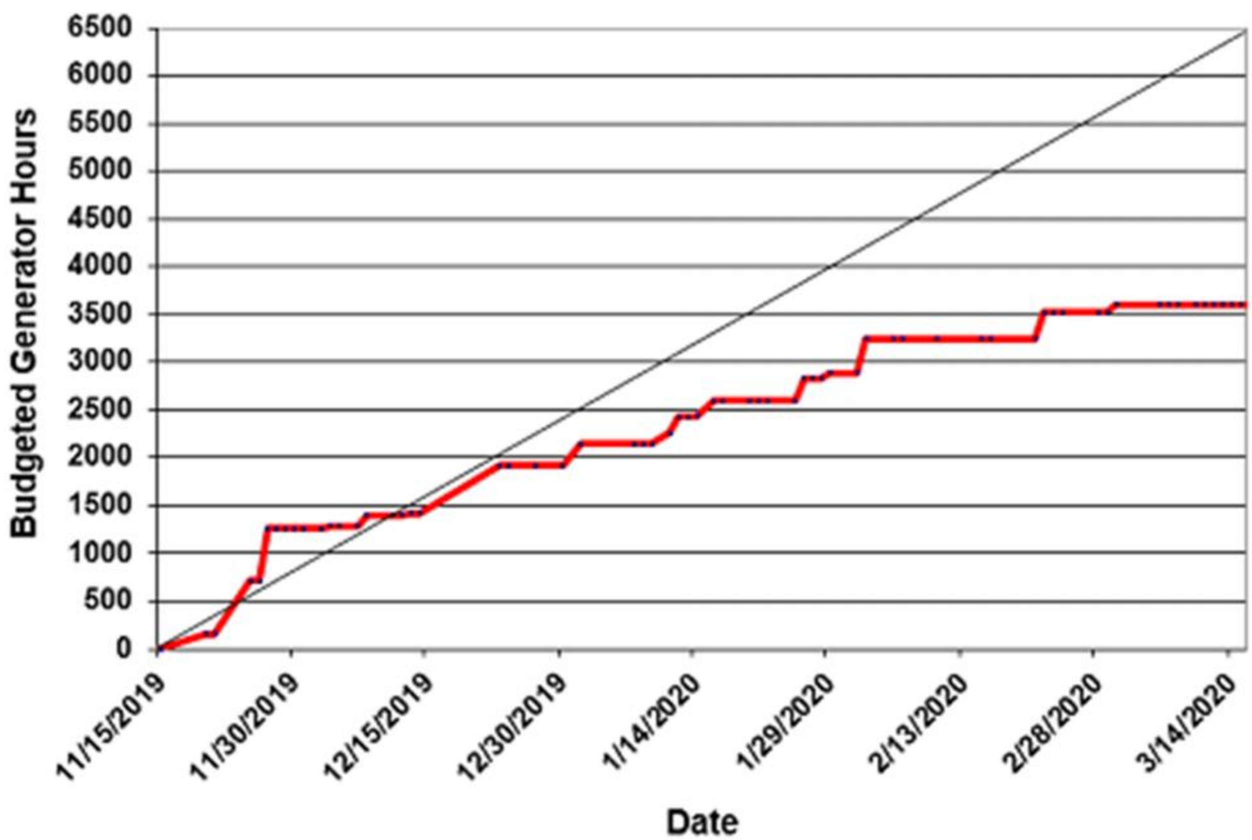

Figure 4.1 Cumulative and budgeted seeding hours for the southern/central Utah core program during the 2019-2020 season. Red line shows actual usage this season, while the black diagonal line depicts a linear usage of budgeted hours.

Table 4-1
Storm dates and generator usage, 2019-2020 season

Storm No.	Date(s)	Number of CNG Sites	Number of Generator Hours		
			Primary Contract	Lower Basin Extension	Total Hours
1	November 20-21	10	156.5		156.5
2	November 25-26	37	555		555
3	November 27-30	34	548.25		548.25
4	December 4-5	2	29.5		29.5
5	December 8-9	13	105.75		105.75
6	December 13-14	1	20.5		20.5
7	December 23-25	21	500.5		500.5
8	January 1-2	18	228.25		228.25
9	January 11	21	115.25		115.25
10	January 12-13	14	166		166
11	January 14	4	10.5		10.5
12	January 16-17	13	159		159
13	January 26-27	24	236.5		236.5
14	January 30	9	56		56
15	February 2-3	29	358		358
16	February 22-23	22	270		270
17	March 1	11	84.25		84.25
18	March 8	1	2.5		2.5
19	March 18	18		142	142
20	March 19-20	20		478.75	478.75
21	March 21	2		8.75	8.75
22	March 23	3		9.5	9.5
23	March 25-26	15		185	185
24	March 29	6		43.5	43.5
25	April 1-2	18		211	211
26	April 8-9	6		82.5	82.5
27	April 15-16	11		185.75	185.75
Total Hours			3,602.25	1,346.75	4,949

* Seeding funded by the Lower Basin States

As of April 1st, 2020, SNOTEL observations showed variable numbers, with snowpack mostly above the long-term median values and water year to date generally below the long-term mean values. Part of this differences is expected due to the differences between the median (used as a normal for snowpack) and mean (used as a normal for precipitation). The highest percentages overall for the season were in southwestern Utah. The April 1 data are summarized in Table 4-2.

Table 4-2
Snowpack and Precipitation Percentages on April 1, 2020

River Basin	No. of Reporting Stations	Snow Water Percent of Median	Water Year Precipitation Percent of Average
Tooele County	3	104%	80%
Price - San Rafael	6	101%	89%
Beaver River	2	97%	87%
Upper Sevier River	11	113%	94%
Southwestern	8	138%	101%

Figure 4.2 provides the percent of median values of April 1 snow water content for Utah. Figures 4.4 – 4.6 show the seasonal snow water content and cumulative water year precipitation and normals at Mammoth-Cottonwood in central Utah, Webster Flat in southwest Utah, and Mining Fork in Tooele County (all NRCS SNOTEL sites). Figures 4.3 – 4.5 show October 1, 2019 – April 1, 2020 snow water equivalent, accumulated precipitation, and normal values for three SNOTEL sites.

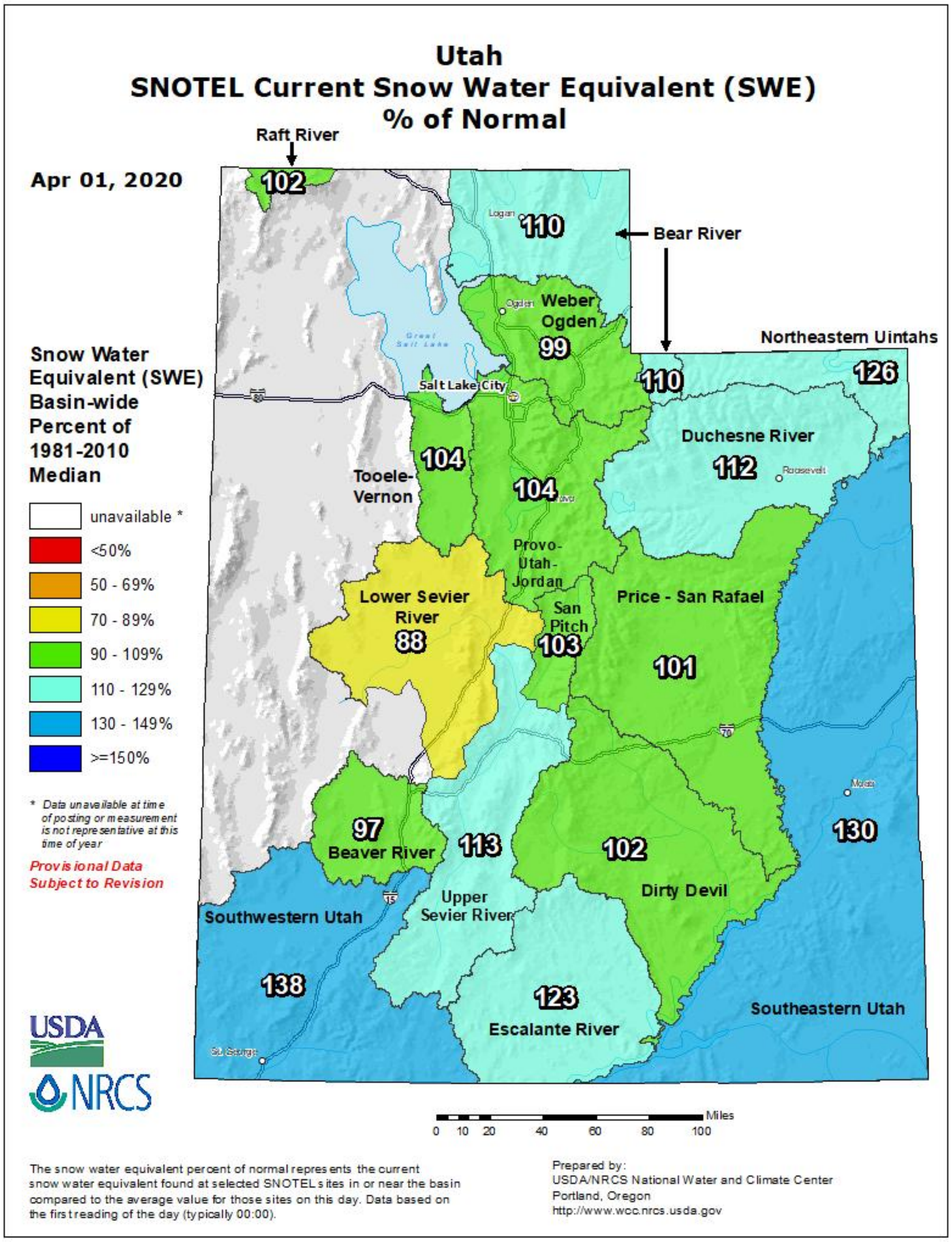

Figure 4.2 Snow water content in Utah on April 1st, 2020 (percent of median)

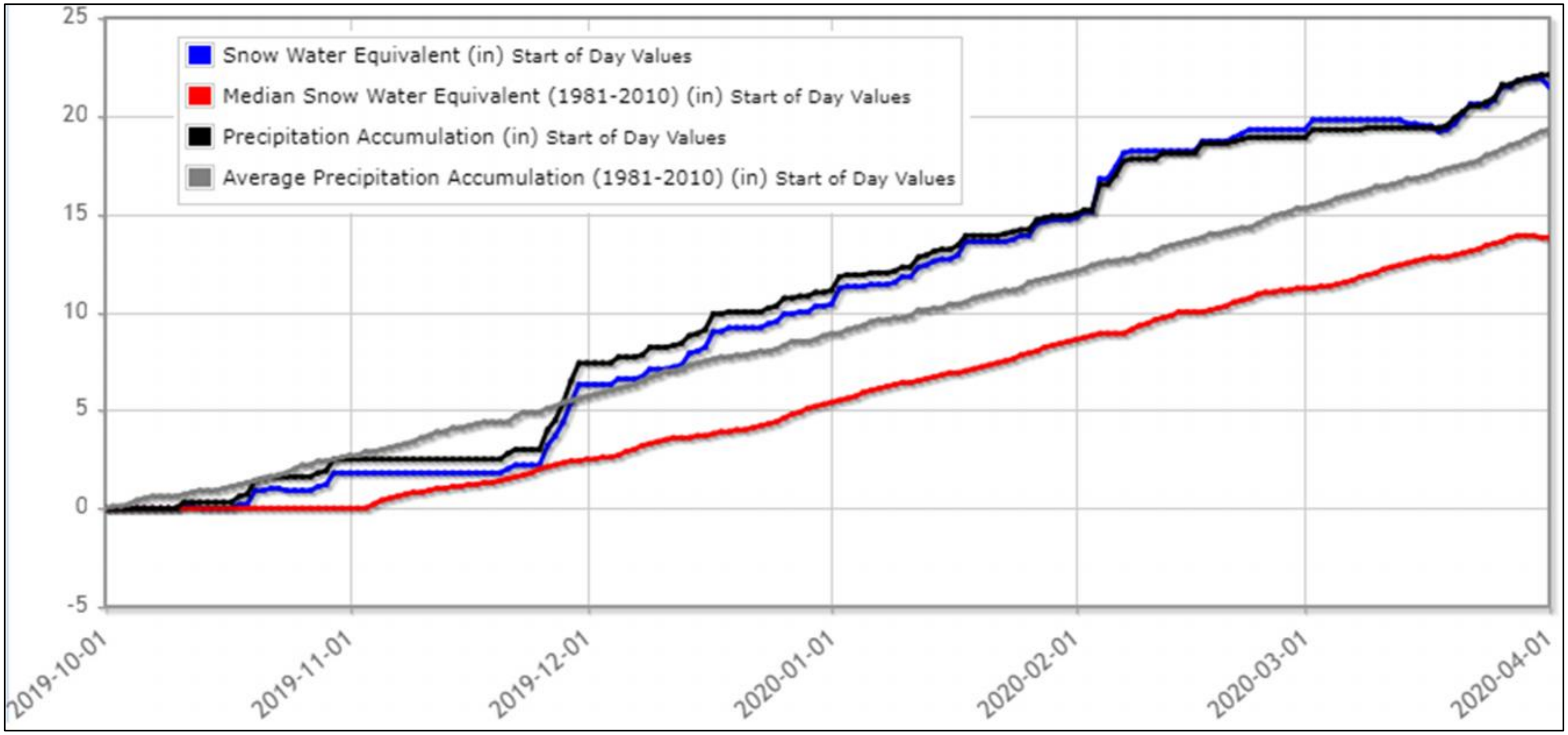

Figure 4.3 **SNOTEL graph for Dry Fork in Tooele County. The black and blue lines represent accumulated precipitation and snow water content for the current season, respectively. The grey and red lines are the corresponding 30-year averages.**

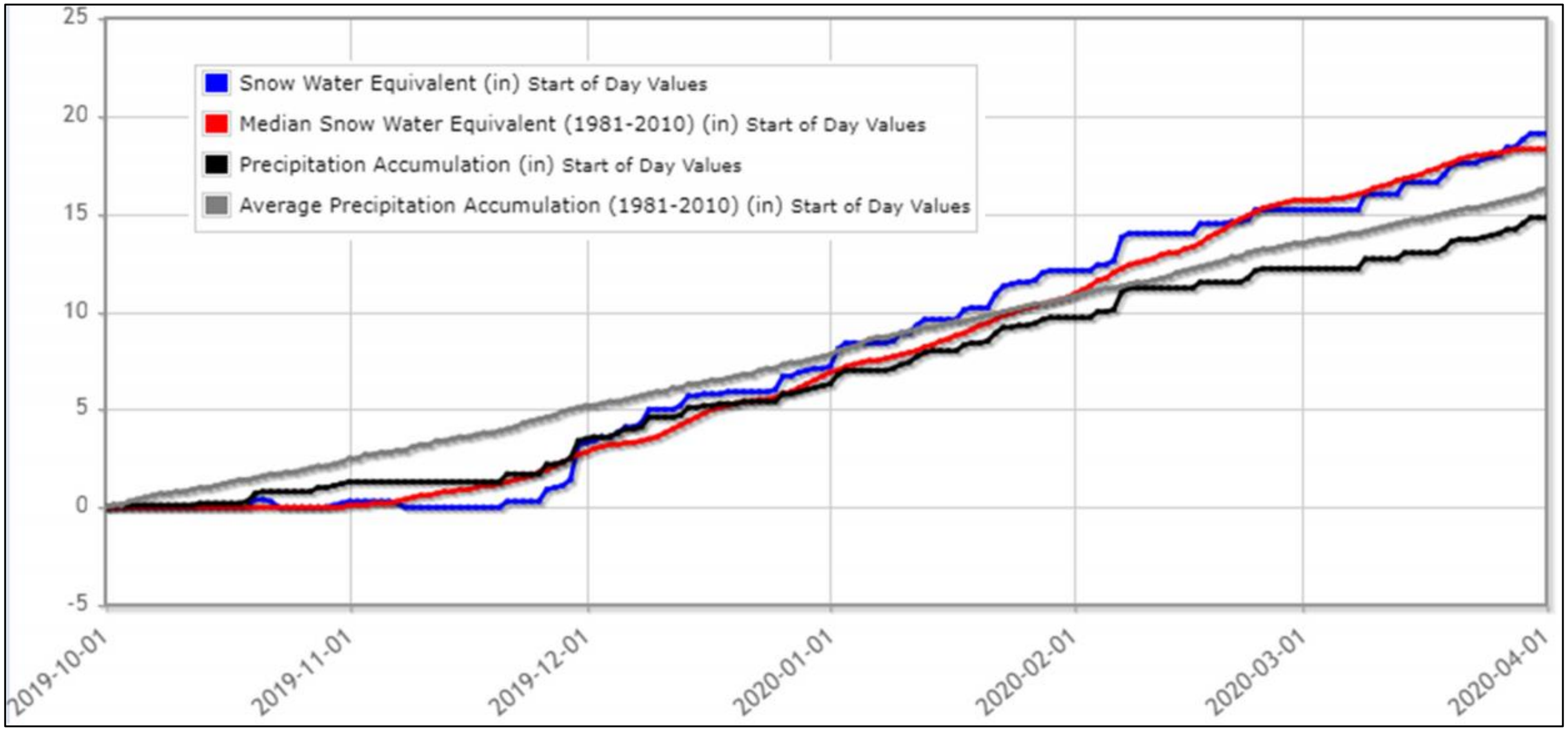

Figure 4.4 **SNOTEL graph for Mammoth-Cottonwood in central Utah. The black and blue lines represent accumulated precipitation and snow water content for the current season, respectively. The grey and red lines are the corresponding 30-year averages.**

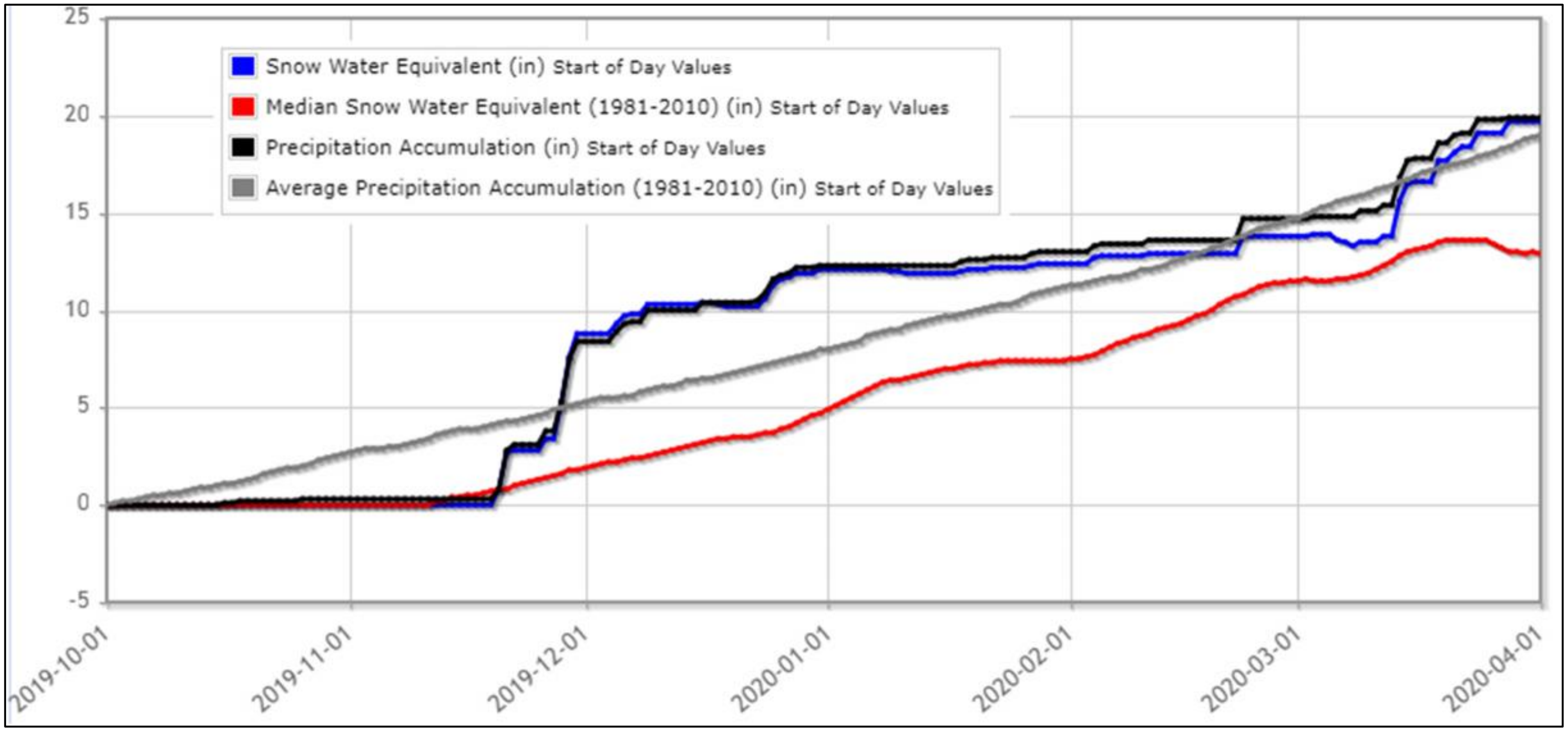

Figure 4.5 SNOTEL graph for Webster Flat in southwestern Utah. The black and blue lines represent accumulated precipitation and snow water content for the current season, respectively. The grey and red lines are the corresponding 30-year averages.

4.1 Operational Procedures

In operational practice, an approaching storm was monitored at the NAWC operations center in Sandy with the aid of continually updated online weather information. Outside typical business hours, NAWC's meteorologists monitored the weather information using computer systems at their residences. If the storm parameters met the seedability criteria presented in Table 2-1 of Section 2 and no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators was ignited and adjusted as conditions required. Seeding continued as long as conditions were favorable and precipitating clouds remained over the target areas. In a normal sequence of events, certain generators would be used in the early period of the storm passage, some of which might be turned off as the wind directions at various levels of the atmosphere changed, while others were used later to target the area in response to the evolving wind pattern. Some generator sites, due to their location, were used in a wider variety of wind flow situations than others and were thus used more often.

4.2 Operational Summary

A synopsis of the atmospheric conditions during operational seeding periods is provided below. All times reported are local, either in MST or MDT. This synopsis describes seeded storm periods, as well as some significant storm periods that were not seeded.

November 2019

November was quite wet in far southern Utah, with over twice and locally around three times the normal monthly precipitation. Central portions of the state were quite variable, with above normal totals in most areas but below normal precipitation just north of the target areas and in the vicinity of Tooele County. There were no seeding opportunities during the early season extension period which occurs from November 1-15, as the weather was essentially completely dry during the early and middle portion of the month. However, some significant seeding opportunities occurred (for the core program) during the second half of November. Figure 4.6 shows precipitation as a percentage of the average (mean) monthly values across the region in November.

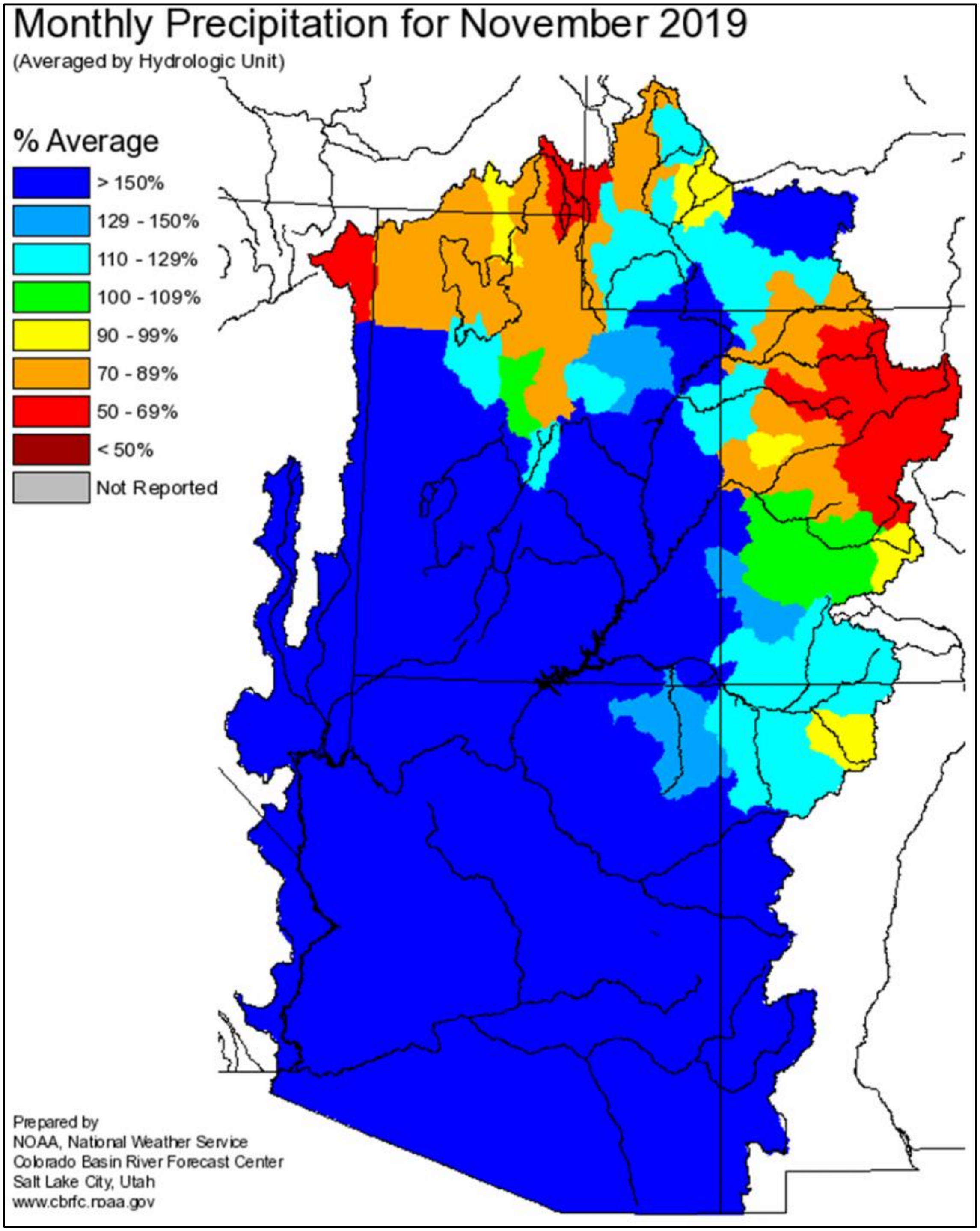

Figure 4.6 November 2019 precipitation, percent of normal

The first seeding opportunity of the season occurred on November 20th-21st, as a closed low moving from southern California into the Four Corners region broke a long dry period in southern Utah. Daily rainfall records were broken in far southwestern Utah, with over an inch of rainfall in areas around St. George and Cedar City. The 700 mb temperature dropped to around -5°C to -6°C in association with the core of this system. Seeding began on the evening of November 20th for higher mountain areas of southern Utah in a south to southeast wind pattern and continued until midday on November 21st when conditions began to dry across the area. A significant amount of icing was observed at Brian Head during portions of this event with approximately a cycle per 15-minute period for a time on the morning of the 21st. Skyline recorded two icing cycles, one on the afternoon of the 20th and one in the early morning of the 21st. Precipitation was generous over much of the target areas, ranging from roughly a half inch of water equivalent in more northern portions of the target areas to over two inches in portions of the southern mountains.

Two major storm events affected the area during the last five days of November, which ultimately turned a very dry month into one that ended up with over 150% of the monthly average precipitation in most of southern Utah. A strong cold front moved across Utah from northwest to southeast on the 25th, with the 700 mb temperature dropping from roughly 0°C to -10°C with the frontal passage. Orographic snowfall then continued in some areas on the morning of November 26th in northwesterly flow, with the 700-mb temperature falling as low as -14°C. Widespread seeding occurred from about midday on the 25th through the morning of the 26th in some areas, ending around midday. Precipitation amounts with this storm period ranged from about 0.5 to 1.0 inches of water equivalent in most of the target areas. Significant icing, including a few double cycles per 15-minute period, was observed at Brian Head from about 2000 MST on November 25th to around 0400 MST on the morning of the 26th, even with cold site temperatures near -16°C. Skyline observed one icing cycle shortly before midnight. Figure 4.7 is an image of data from the Brian Head ice detector site for a portion of this event.

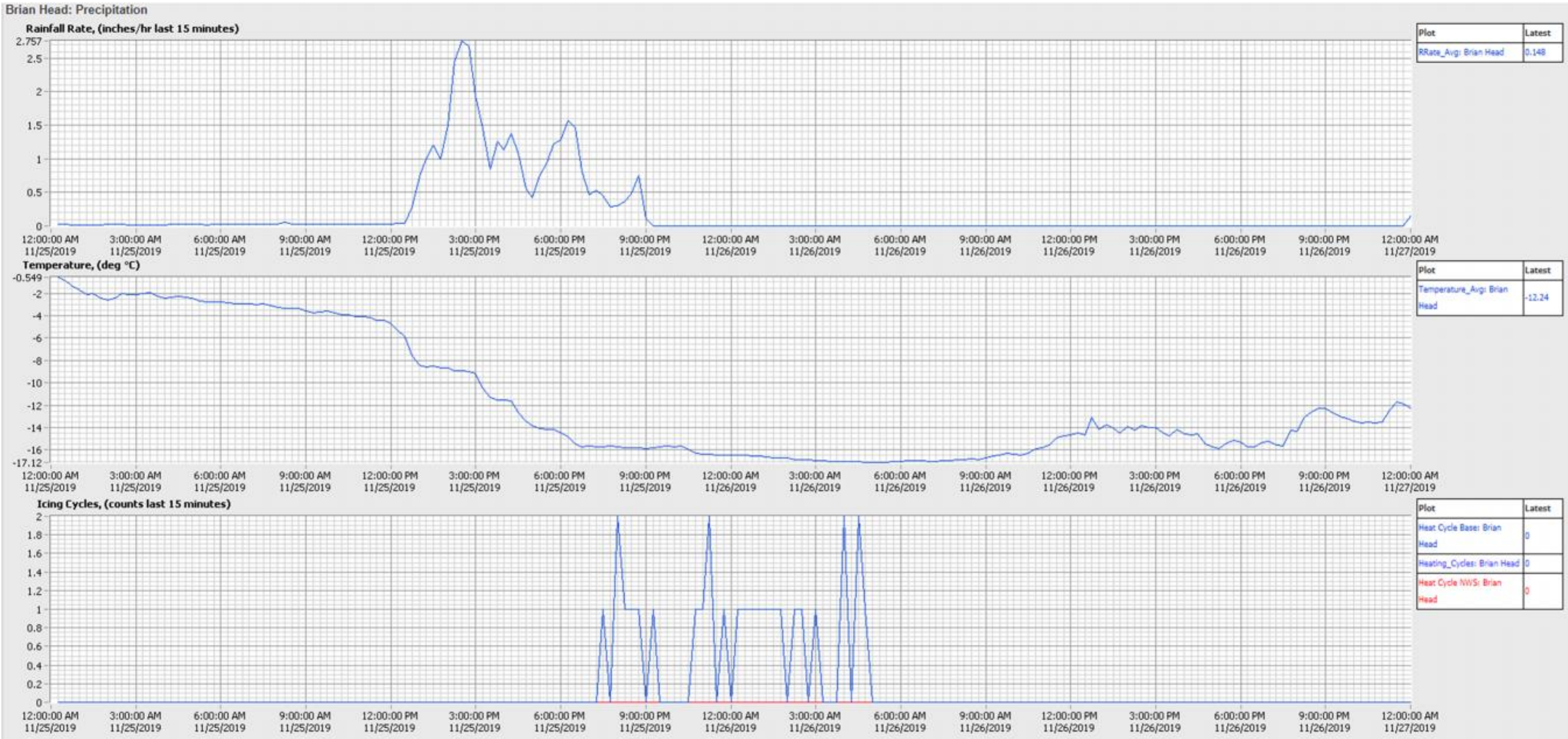

Figure 4.7 Brian Head precipitation rate (top), temperature (center) and icing cycles (lower panel) for the November 25-26 storm event. This figure shows a precipitation period accompanied by falling temperatures, followed by a period of significant icing.

A large, deep trough developed near the west coast on November 27th -28th, with increasing moisture from a subtropical plume over northern Mexico and into Arizona and southern Utah. Seeding began from a few sites on the evening of the 27th in far southern Utah, although winds were slightly east of southerly and temperatures warming to around -5°C at 700 mb, which limited seeding opportunity. Further north, light snowfall was originating from a high cloud deck with some stability in the lower levels, which was not favorable for seeding, although seeding continued in southern Utah through the night of the 28th. A frontal (baroclinic) zone remained essentially stalled over Utah into the night of November 28th-29th, and was a focus of continued moderate to heavy snowfall over much of the southern and central portions of the state, with the 700 mb temperature generally remaining around -4°C to -6°C. Sporadic icing was observed at Brian Head, mainly around midday on the 28th with a period of multiple cycles per 15-minutes. On November 29th, winds became more westerly as the colder portion of the trough moved across the area. The 700 mb temperature cooled to around -12°C over much of the state and snowfall became more convective and orographic in nature. Seeding operations shifted into central Utah based on the change in storm characteristics and wind direction. Significant icing activity was observed at the Skyline site during this latter portion of the event from the afternoon of the 29th into the morning of the 30th, including one multiple cycle per 10-minute period there, with some additional cycles at Brian Head as well. Snowfall finally tapered off statewide on the morning of the 30th and seeding operations ended. Precipitation totals for the November 27th- 30th period ranged from about 1.5 inches to as much as 6 inches of water equivalent, with heavier totals generally favoring the southern mountains. Both late November seeded events (November 25th-26th and November 27th-30th) had the highest seeding totals of any storm events this season, each having well over 500 generator hours.

December 2019

December proved to be another wet month in far southern Utah, and generally near normal elsewhere. There were four seeded events during the month, some of which were very limited in scope while others were more significant. Figure 4.8 shows December precipitation patterns as a percentage of the monthly average.

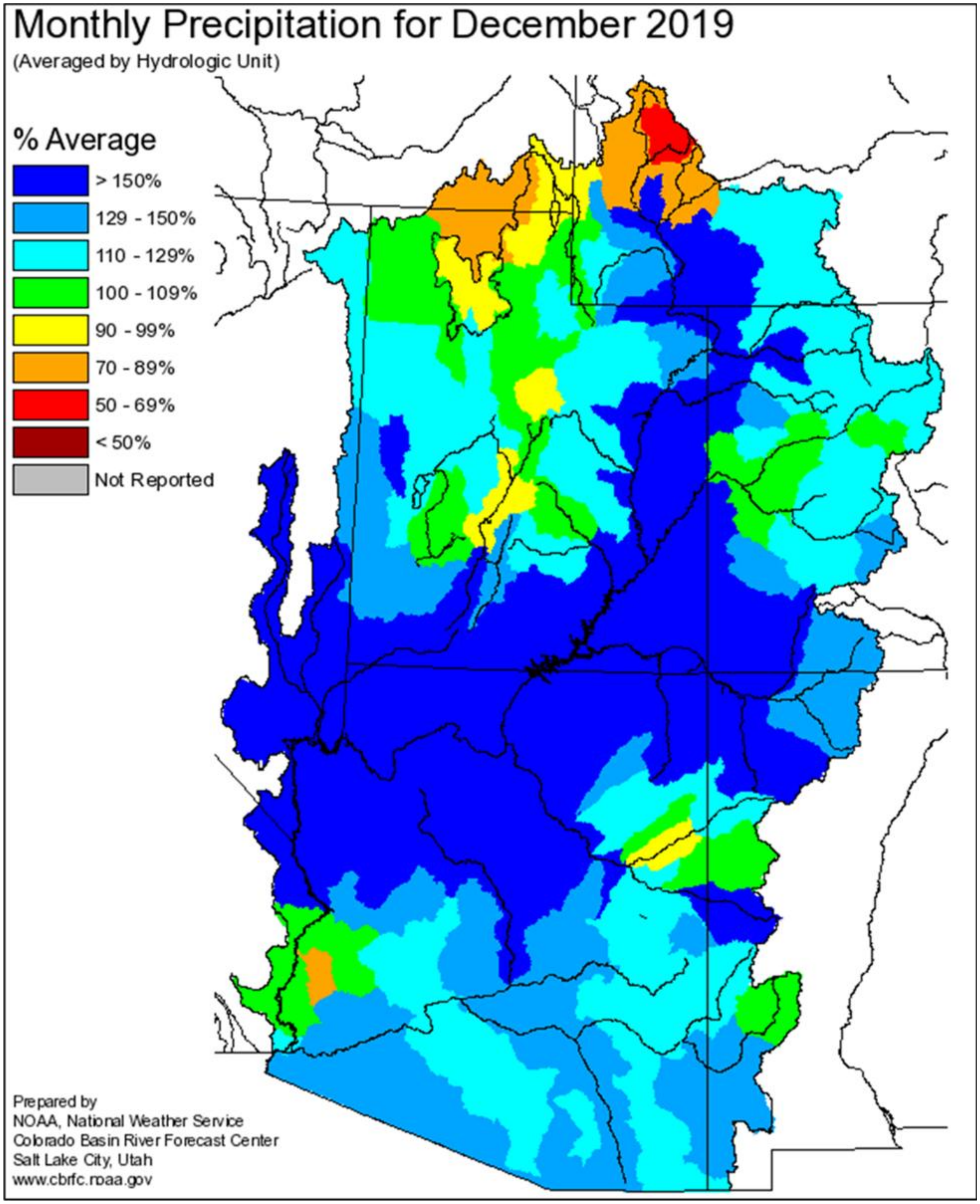

Figure 4.8 December 2019 precipitation, percent of normal

A storm system moved eastward from California into the Great Basin on December 4th, drawing significant moisture northward from the low-level remnants of a subtropical moisture plume to the south of Utah. Temperatures over Utah were mild, generally warmer than -5°C at 700 mb although cooled to near the level on the night of December 4th-5th. Due to the warm temperatures, combined with stability in the lower levels of the atmosphere over most of the state, seeding was only feasible using a couple of high-elevation sites near Brian Head which were near to above the -5°C temperature height. Due to a southerly wind direction, these sites could potentially seed a significant area to the north. This very moist storm event resulted in significant icing activity at both ice detector sites beginning on the evening of December 4th at Brian Head and just after midnight at Skyline. Consistent icing continued until about 0600 MST on the 5th at Brian Head and until about 1800 MST at Skyline. At the Brian Head site, the icing was associated with a site temperature of between -5°C and -7°C which was cold enough to support seeding operations there. Precipitation totals with most of this event were around a half inch in most of the target areas except an inch or more in some southern mountain areas in the Brian Head vicinity. Seeding ended around 0900 MST on December 5th as skies had partially cleared in the Brian Head area at that point.

A weak cold frontal boundary and cooling aloft on December 8th brought convective showers and some thundershowers to portions of central and southern Utah, focused on the south. Although 700 mb temperatures were on the warm side, the relatively strong convective activity made conditions favorable for seeding operations in southern portions of the state during the afternoon and early evening hours. Following this, the temperature cooled to around -8°C at 700 mb and some light orographic snowfall occurred in central Utah on the night of December 8th-9th. This resulted in a seeding opportunity for northern portions of central Utah overnight, with snowfall and seeding ending early on the 9th. At Brian Head, a period of icing activity was observed early on the 8th, and Skyline recorded a few periods of icing activity from the early morning hours to the evening hours on the 8th. Precipitation totals were somewhat variable, from as little as 0.2 inches in portions of the target up to nearly an inch in some southwestern mountain areas, and generally averaging near 0.5 inches.

A cold front crossed Utah on December 14th with scattered areas of snow. Given winds, temperatures, and some other factors, seeding opportunity was limited, but seeding was conducted at Brian Head from midday on the 14th until the morning of the 15th. Significant and consistent icing was noted at Skyline through most of the 14th (although with warm temperatures, around -3°C) and mainly from the morning through early afternoon at Brian Head with a site temperature around -5°C. Precipitation totals were around 0.5 inches in much of the target area, , and lesser totals were observed in the southern mountains.

A large trough with several embedded waves produced significant precipitation and seeding opportunity on December 23rd-24th. Temperatures were initially too warm on the 23rd but had cooled enough by late afternoon and evening for seeding to begin in some portions of central and southwestern Utah. Precipitation continued into the morning of the 24th, with a brief break before it increased again from the southwest later in the day. Snowfall and seeding ended late evening on the 24th in southwestern Utah and continued overnight in central Utah, ending early on the 25th. Although temperatures were on the warmer end of the seeding temperature range during most of the period, cooling to around -7°C at 700 mb occurred toward the end of the seeded period. Precipitation amounts during this time period generally ranged from about 0.5 inches up to around 2.0 inches, with heaviest amounts in the southwestern mountains near Brian Head. Significant icing was observed at Brian Head, including a few multiple cycles, mainly on the night of December 24th-25th (Figure 4.9). Skyline recorded three icing cycles early to midday on the 25th, near to just after the end of the seeded period. Due to the duration and extent of this storm, a total of 500 generator hours of seeding were conducted, making it one of the more heavily seeded events of the season.

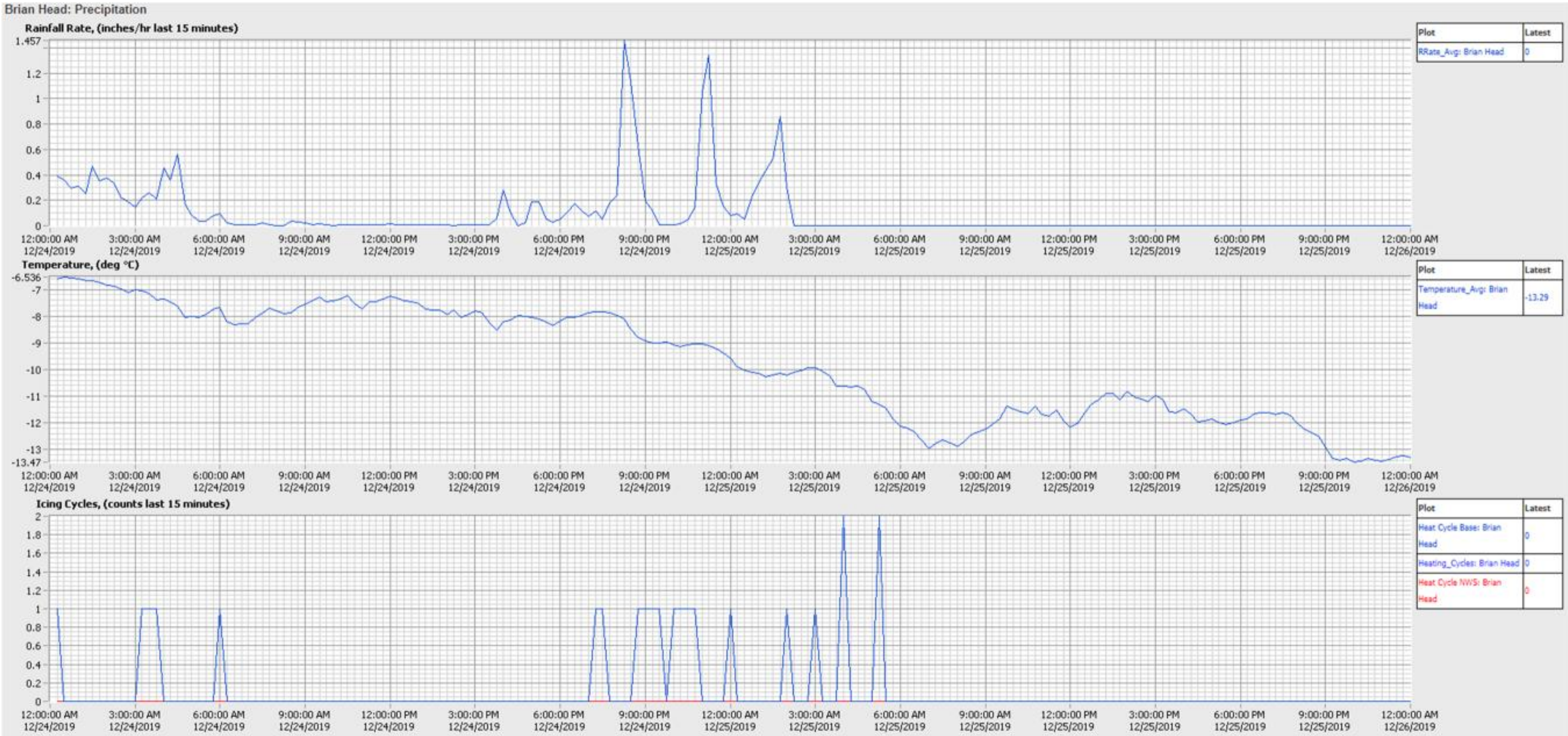

Figure 4.9 Brian Head precipitation (upper panel), temperature (center), and icing (lower panel) for December 24-25. Precipitation and icing periods were intermittent, with temperatures in a favorable range of -8°C to -13° C.

January 2020

January's precipitation patterns were essentially the opposite of the beginning of the season, with the southern part of the state being quite dry, and generally near normal (although quite variable) precipitation in northern portions of the target areas. There were regular storm events during the month, although some of these were minor and limited to northern portions. There were a total of seven seeded storm periods in January. Figure 4.10 shows the monthly precipitation as a percentage of normal in January.

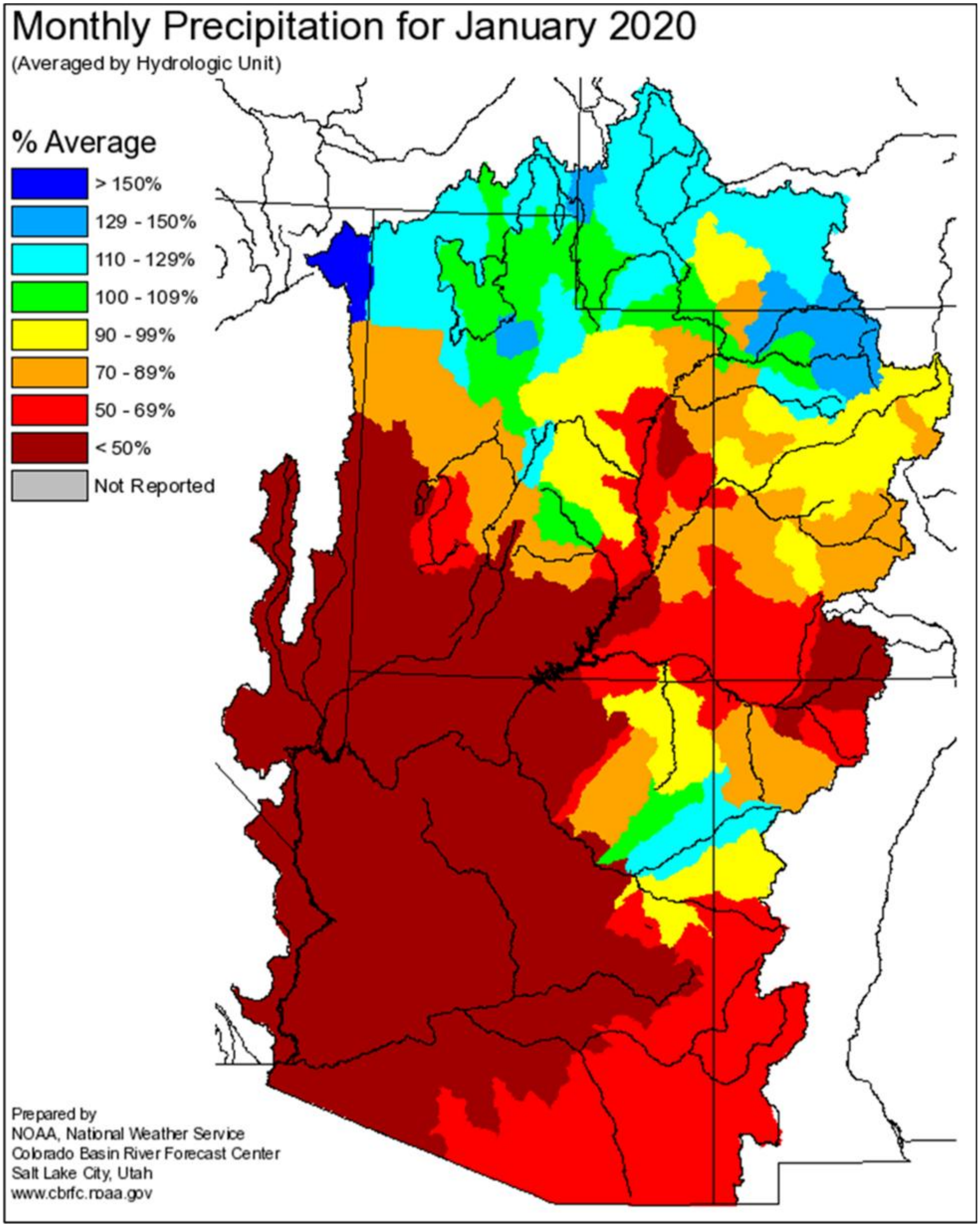

Figure 4.10 January 2020 precipitation, percent of normal

A fast-moving shortwave trough moved into Utah on January 1st, bringing a seeding opportunity for Tooele County as well as portions of central Utah beginning later in the day. The 700-mb temperature cooled to below -5°C by late afternoon or early evening over these areas in northwesterly flow and continued to cool overnight to near -10°C by morning. Strong winds and warm temperatures made seeding conditions generally poor further south, although significant icing was observed at Brian Head during the afternoon and evening of January 1st. Skyline also had a period of afternoon and early evening icing with site temperatures near -4°C. Precipitation ended early on January 2nd and seeding ended that morning as well. Precipitation totals ranged up to about an inch in portions of Tooele County and central Utah, although tapered off rapidly further south to essentially nothing in the far southern mountains.

Another fast-moving system in northwesterly flow allowed for a fairly brief period of seeding for Tooele County and northern portions of central Utah during the late afternoon and evening of January 11th. The 700 mb temperature was near -10°C and SLW appeared quite limited with most precipitation originating in a relatively thin, higher cloud deck. Skyline recorded an icing cycle in the evening and a few additional cycles overnight, while Brian Head did not observe any icing. Precipitation totals ranged from about 0.5 inches in northern portions of the target area to zero once again in far southern Utah.

An active pattern continued during the January 12th-14th period in mainly the northern portions of the area, with another seeded storm event in Tooele County and northern portions of central Utah on the night of the 12th-13th. Winds were mainly southwesterly on the night of January 12th-13th with a 700 mb temperature around -12°C in the seeded areas. Seeding ended across these areas on January 13th, but a portion of the system affected northern Utah on the 14th with a frontal passage and some very brief seeding operations in Tooele County. No icing was recorded at Skyline or Brian Head during these time periods, and precipitation amounts were limited with a quarter to half inch in northern (seeded) portions while it remained basically dry for the southern half of Utah.

A large trough moved into the region on the night of January 16th-17th, with strong winds, snow and temperatures falling below -5°C at 700 mb late that night. Seeding began overnight and continued until midday on the 17th, by which point winds had become west-northwest and the 700 mb temperature had fallen below -10°C. Precipitation mostly ended around midday. Seeding was not conducted in Tooele County due to strong winds and the system mainly affected northern half to two-thirds of the state once again, so seeding operations for this program were limited to portions of central Utah. Both Skyline and Brian Head recoded some icing activity on the morning of the 17th, with the icing briefly heavy at Brian Head. Precipitation amounts ranged from about 0.5 – 1.0 inches in northern portions to around a quarter inch in the far south. The timing of the frontal passage was not conducive to activating seeding sites in the south.

A weak but somewhat moist system moved from Nevada into Utah on the night of January 26th-27th. Temperatures were above -5°C at 700 mb initially, but fell into a favorable range overnight, dropping to around -8°C by the morning of the 27th. Precipitation became fairly widespread overnight, with winds from the west to northwest. Seeding ended on the morning of the 27th as precipitation tapered off for most areas. Skyline recorded five icing cycles overnight (Figure 4.11), with more extensive icing between about 2100 and 0900 MST at Brian Head with a few double cycles per 15-minute period there. Precipitation amounts with this system were generally in the 0.25 to 0.50 inch range.

A weak system crossed Utah in north-northwesterly flow on January 30th, with a 700 mb temperature generally between -7°C to -9°C. This system produced scattered snow showers, and seeding was conducted from some sites in western and southwestern portions of the state generally near the I-15 corridor. There was a notable period of very heavy icing recorded at Brian Head from roughly 1000 to 1600 MST, with up to as many as five cycles per 15-minute period early in the afternoon. This was observed in association with snow showers and a temperature near -9°C at the Brian Head site, suggesting excellent conditions for seeding during that time period. Skyline only recorded one icing cycle during this time. Precipitation amounts were very light and scattered with this system, with generally around 0.1 inches of water content at some SNOTEL sites.

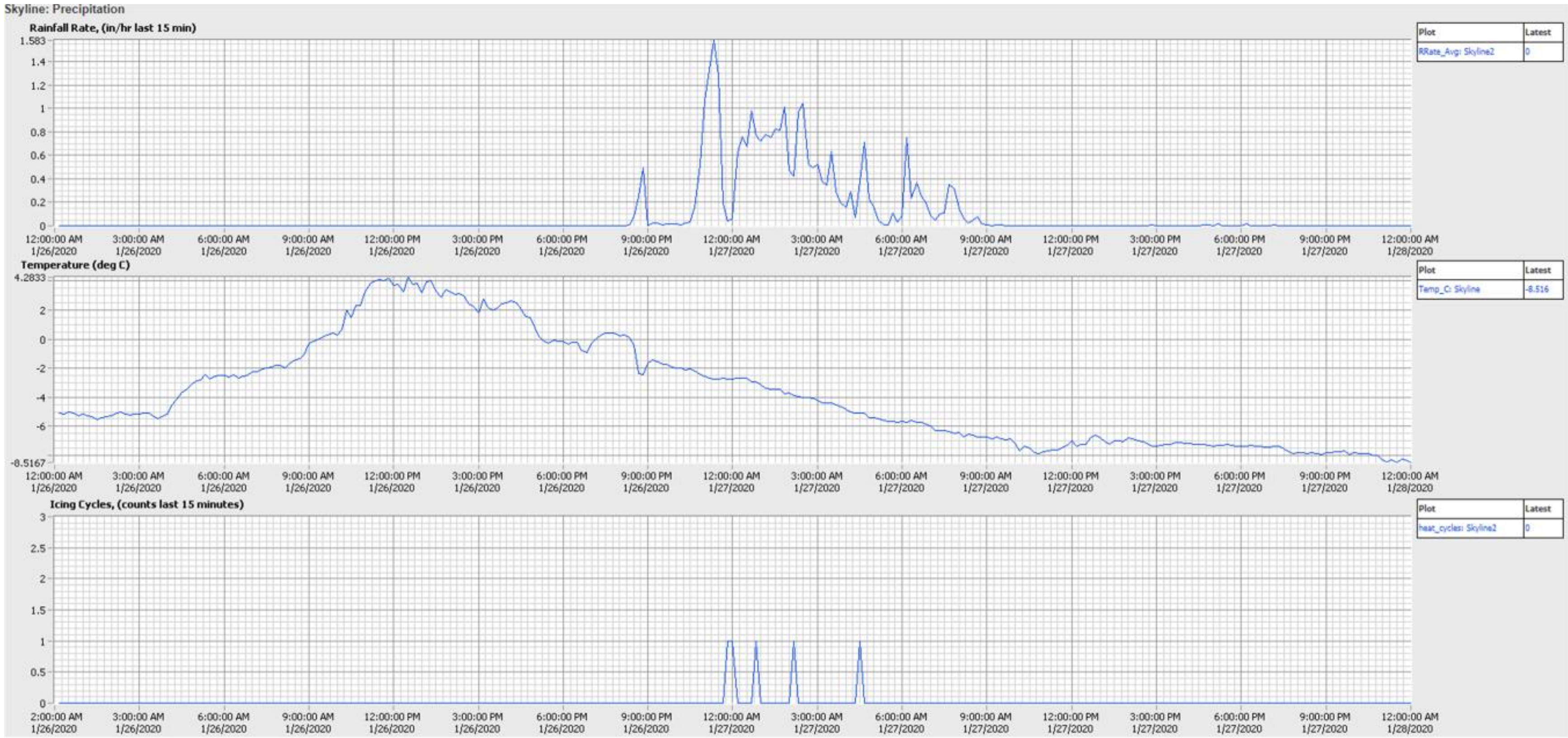

Figure 4.11 Skyline precipitation (upper panel), temperature (center) and icing (lower) for January 26-27. This storm period was characterized by some icing cycle during a precipitation period at Skyline, with steadily falling temperatures.

February 2020

February precipitation was below normal area-wide, with infrequent storm events. There were only two seeding opportunities, although both were fairly significant. Figure 4.12 shows the February precipitation pattern across the region in comparison to average values.

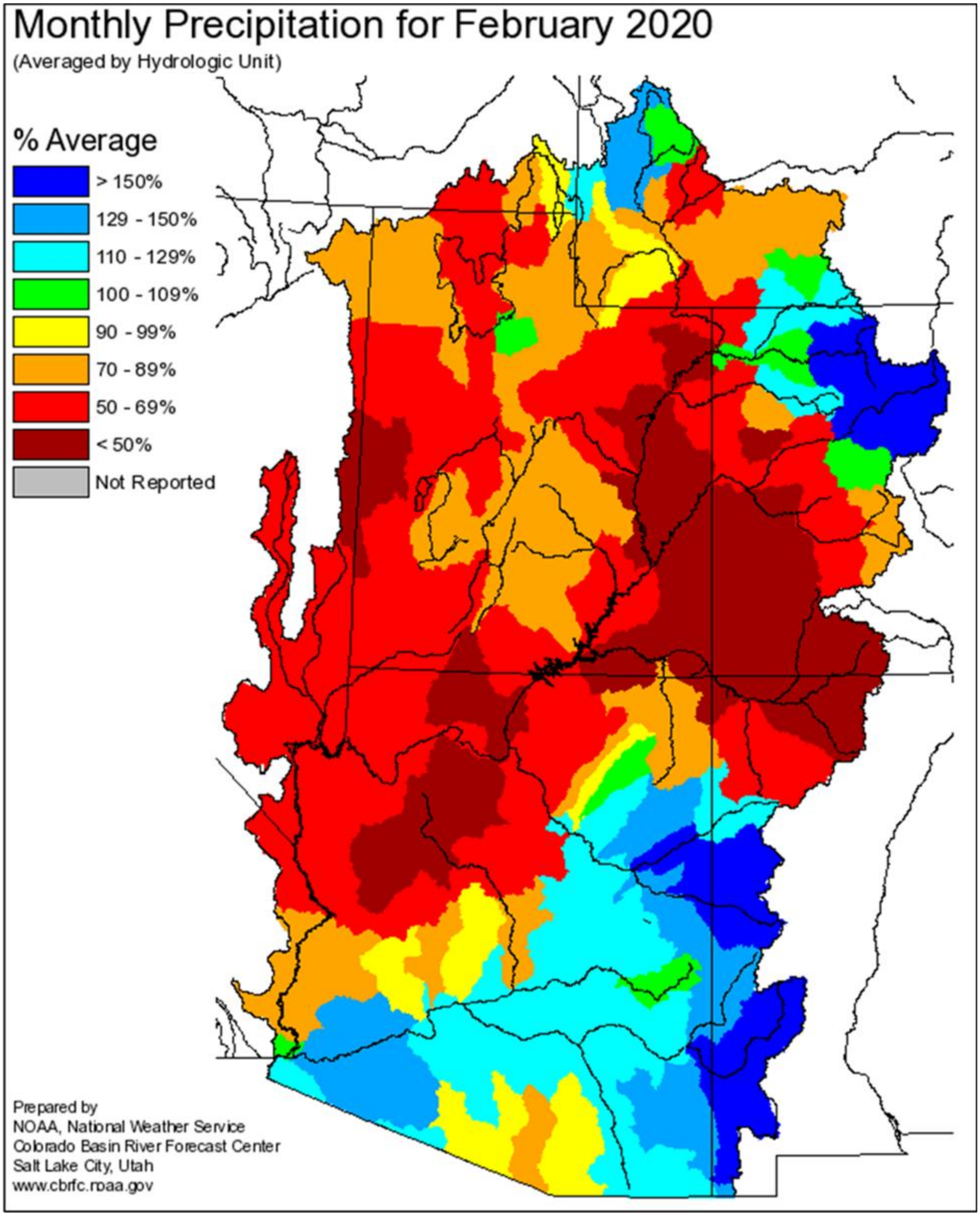

Figure 4.12 February 2020 precipitation, percent of normal

A strong, cold low pressure trough brought a major snow event to most of the state beginning on the night of February 2nd-3rd and continuing through most of the day on the 3rd. Many areas in northern and central Utah received over a foot of snow accumulation with this storm, particularly along the I-15 corridor. Seeding began on the night of the 2nd, mostly ending on the morning of the 3rd but continuing until midday in some areas. It appeared that SLW was somewhat limited with this storm, and very cold temperatures, falling below -15°C at 700 mb on February 3rd were a factor. The only icing observed was at Brian Head beginning late on the 3rd, on the tail end of the event and with a very cold site temperature (below -20°C). Seeding with this event was more widespread in Tooele County and central Utah although operations were conducted in parts of the south as well. Precipitation totals ranged from 1.5 inches or more of water equivalent in Tooele County to over 0.5 inches in portions of central and southern Utah, with generally lighter totals in eastern and southern portions of the target areas.

Following this event, there was a period of strong north-northwesterly flow in a warm advection pattern on February 5th-6th that brought localized heavy snowfall amounts to certain orographically favored areas, including Tooele County and portions of central Utah. However, temperatures warmed above -5°C at 700 mb and the lower level atmosphere was stable, preventing any good targeting options. Widespread avalanche warnings were also in effect for some of these areas due to heavy snow on top of lighter, dry snow, and major avalanches were reported in some areas. No seeding occurred during the February 5th-6th storm period.

The only other seeding opportunity in February was with a closed low that moved from California to near the southern border of Utah on February 22nd-23rd. Temperatures were warm initially but seeding began on the evening of the 22nd as convective showers developed, associated with cooling aloft as the low approached from southern Nevada. Seeding was conducted overnight in west-central and southwestern Utah. The low moved into the Four Corners region on February 23rd and winds became northerly as precipitation ended over Utah, with seeding operations ending during the morning hours. The 700 mb temperature was around -5°C to -6°C with the passage of this low over the area. Brian Head recorded sporadic periods of icing overnight and through the morning hours of the 23rd, with no icing at Skyline. Precipitation totals were significant, generally ranging from 0.5 to 1.0 inches of water equivalent with the heavier totals in the southern mountains. Figure 4.13 shows data from the Brian Head icing site with this event.

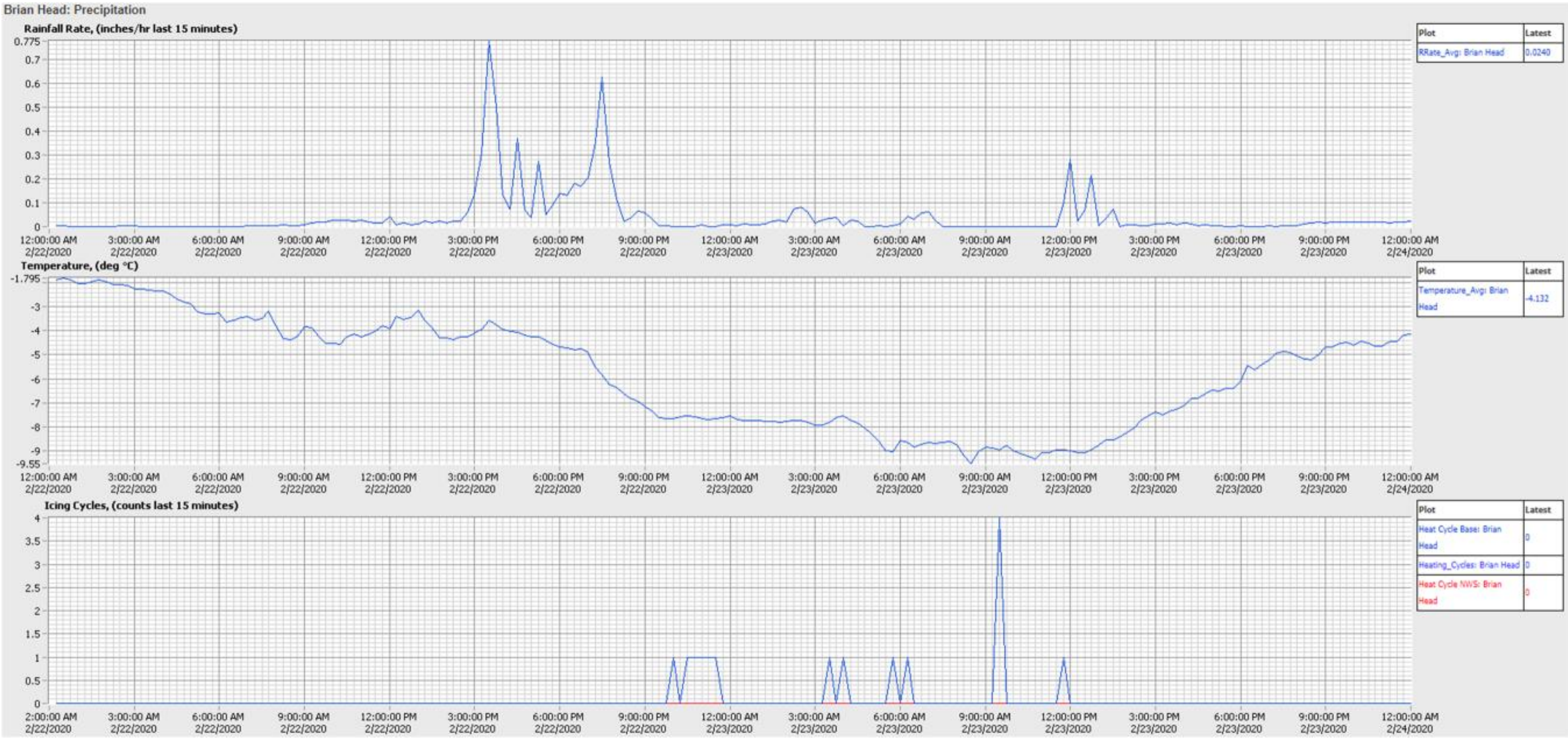

Figure 4.13 Brian Head precipitation (upper panel), temperature (center) and icing cycles (lower) for February 22-23. Intermittent, mostly single icing cycles were observed with one period having two cycles. Icing occurred after the main period of precipitation.

March 2020

March precipitation was below average in most areas, except well above average in the southwestern corner of the state. Southern portions of the state enjoyed a fairly active storm track, with much drier conditions in the north as shown in Figure 4.14. There was a total of eight seeded storm periods in March.

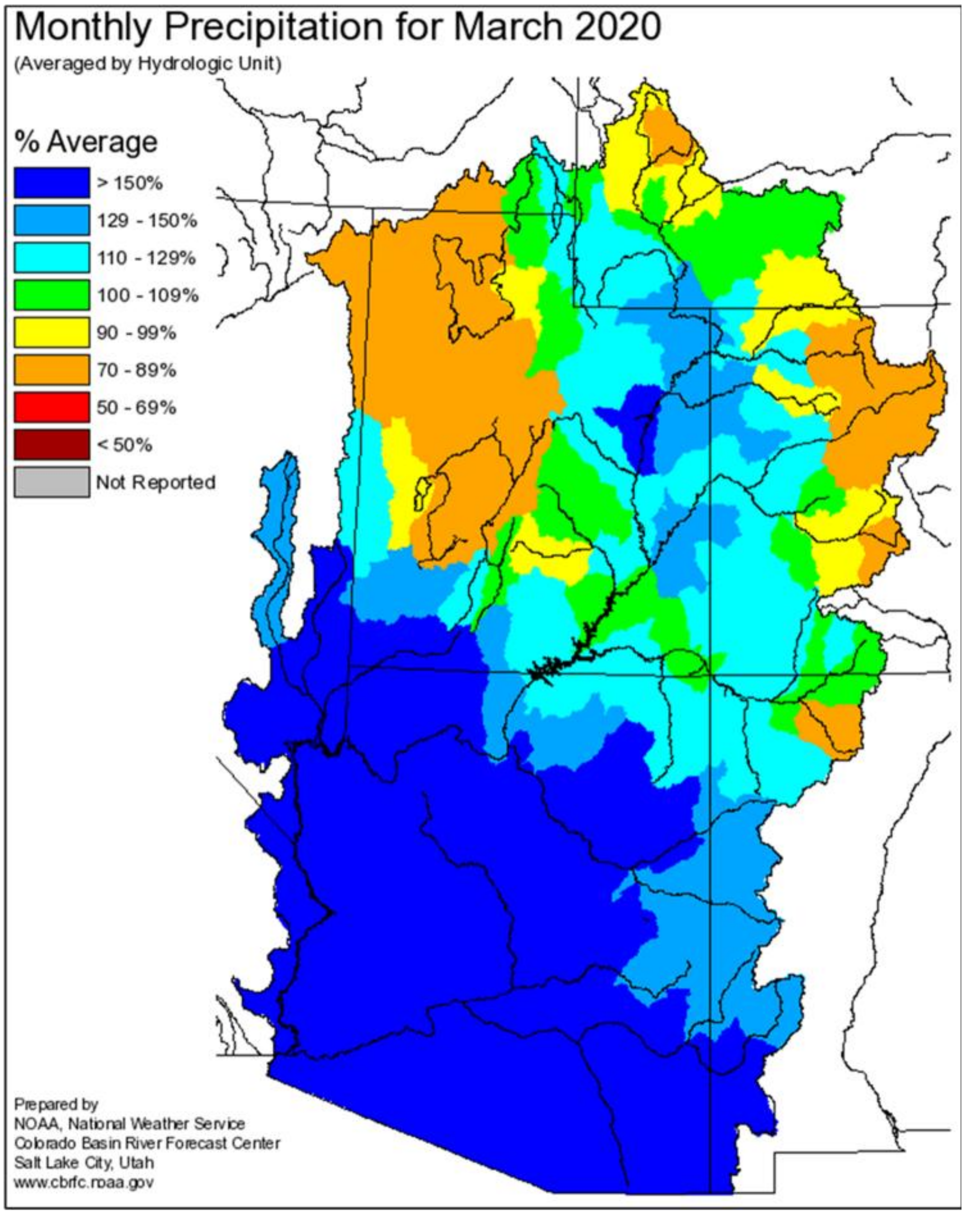

Figure 4.14 March 2020 precipitation, percent of normal

A splitting storm system on March 1st affected northern portions of the state including Tooele County initially, and seeding began there in the morning with frontal snow bands and 700 mb temperatures below -5°C. While the rest of the state remained above this temperature threshold, convective activity began to develop in southwestern Utah during the afternoon and seeding operations became feasible there despite the mild temperatures. As the trough shifted in that direction, seeding ended by early evening in Tooele County and continued through the evening hours in southwestern Utah. Favorable conditions never developed for central portions of the state. The only icing observed was one cycle in the evening at Brian Head. The radiometer located at Brian Head showed modest amounts of liquid water, but up to several thousand feet in depth above the site. Precipitation totals ranged from around a half inch in Tooele County, to less than 0.2 inches in the southwest and near zero in central portions of the state.

A weak system in southwesterly flow resulted in some brief convective activity during the afternoon hours of March 8th. Although temperatures were mild (well above -5°C at 700 mb), seeding was briefly conducted at Brian Head due to the convective shower activity, as well as consistent icing activity at the Brian Head site from the early morning hours up to mid-afternoon. Despite the icing activity, the radiometer site at Brian Head only showed limited moisture, and Skyline had no icing activity. Precipitation totals in most areas were around 0.25 inches or less, although with some locally higher amounts. This was the last seeded storm of the season for the core program, although the Lower Basin Extension areas remained active until mid-April.

A trough moved into the Great Basin on March 18th, with generally light shower activity increasing from southwest into central Utah during the day. The 700 mb temperature cooled into the -6°C to -8°C range. Seeding was initiated in the morning in southwestern Utah and expanded into central Utah by early afternoon. A low pressure center over Arizona became the dominant center of the system by late in the day, with showers gradually decreasing and winds becoming light north to northwesterly in the lower levels overnight. Seeding ended during the evening hours. Brian Head recorded periods of icing activity during the afternoon/evening hours of the 18th and again overnight, with Skyline only recorded icing during the night and morning hours of the 19th following the seeded event. Precipitation totals were quite variable, generally less than 0.4 inches in most of the target areas but locally over 0.5 inches in southern Utah.

A complex trough remained over the western U.S. on March 19th-20th, with scattered precipitation including afternoon and evening convective showers aided by daytime heating on both days. Shower activity was also observed overnight in portions of southwestern and central Utah. The 700 mb temperature ranged from about -6°C to -8°C during this time period, with winds generally light and variable in direction. A good amount of seeding was conducted from the afternoon of March 19 through the evening of March 20th in much of central and southwestern Utah, including Washington County. Some sporadic icing cycles were observed at both Brian Head and Skyline during this period, but icing activity was intermittent and light. Precipitation totals were generally near to under 0.5 inches in most of the target areas with isolated higher totals.

A weak, sheared trough remained over Utah on March 21st. Although precipitation was pretty insignificant, some weak convective showers developed over some southern mountain areas during the afternoon and limited seeding was conducted. Precipitation was fairly localized, with some 0.1 to 0.3 inch totals in the southern mountains. Several icing cycles were observed during the late afternoon and early evening hours at Brian Head with a site temperature around -7°C.

Some brief and limited seeding was again conducted in southern Utah on March 23rd with a low center moving eastward along the southern Utah border. Temperatures were initially on the warm side, but eventually became cold enough in association with some convective activity around the low center. Seeding was conducted during the afternoon hours with convective activity for a few hours. Consistent, light to moderate icing activity was observed at Brian Head during the afternoon and evening hours with a site temperature of -6°C to -7°C. Precipitation totals were around 0.2 inches or less in most portions of the target areas although Webster Flat in the Brian Head area recorded a total of 0.7 inches.

A trough was oriented from the northern Rockies to central California on March 25th, with a frontal zone bisecting Utah. Precipitation began in western portions of the state in the evening as the frontal zone, cooling temperatures and snowfall slowly worked its way south and eastward into the target areas but remained somewhat limited in extent. The system weakened before reaching eastern areas, but light snow showers continued in southwesterly flow on March 26th and seeding continued for much of the target area. The 700 mb temperature was generally around -8°C in association with the seeded portion of the storm event. Snow shower activity ended around sunset and seeding operations were terminated as well. Brian Head recorded consistent icing activity overnight between about 0100 and 0800 MDT on March 26th (Figure 4.15), with one cycle observed at Skyline after 0500 MDT. SNOTEL data showed less than about 0.2 inches in most of the Lower Basin extension target areas, although up to around 0.3 inches in some areas.

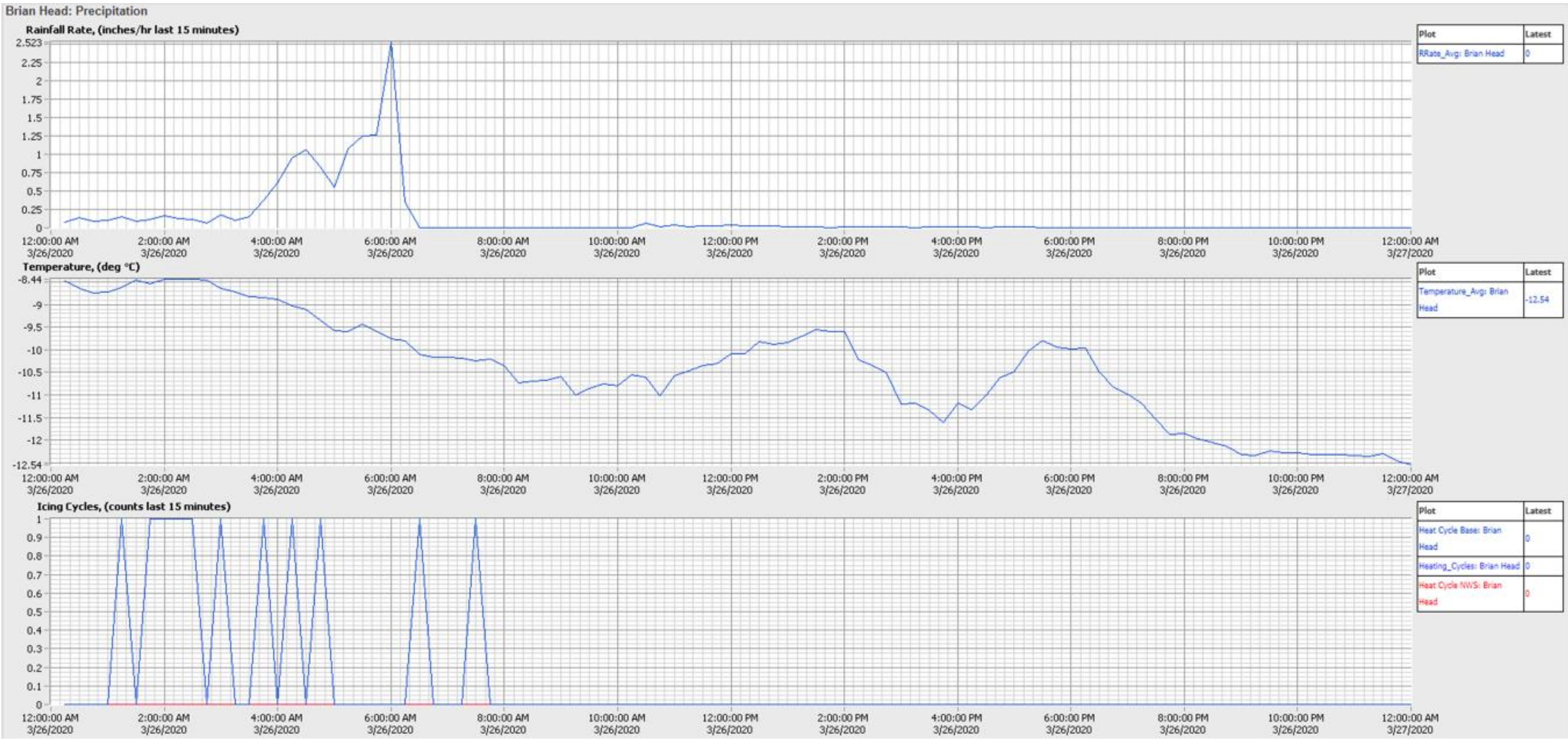

Figure 4.15 Brian Head precipitation (upper panel), temperature (center) and icing cycles (lower panel) on March 26th. Icing was observed in association with a precipitation period early in the day, and temperatures in an ideal range, near -9°C to -10°C.

A disorganized trough moving into the Great Basin on March 29th, in combination with daytime heating, sparked diurnal shower activity and a limited seeding opportunity. The 700 mb temperature was generally around -5°C with light southerly winds. Seeding was conducted in south-central portions of the state from early afternoon until evening. One icing cycle was observed in the evening around 2100 MDT at Brian Head. Precipitation amounts at SNOTEL sites ranged up to about 0.50 inch with this system.

April 2020

April was a very dry month across some portions of Utah and in fact, set a record for the driest April on record at Salt Lake City. The situation was somewhat better in southern Utah although precipitation was still well below average. Figure 4.16 shows precipitation patterns in April. The month of April did provide three seeding opportunities for the Lower Basin Extension portion of the program, which was active through April 15th.

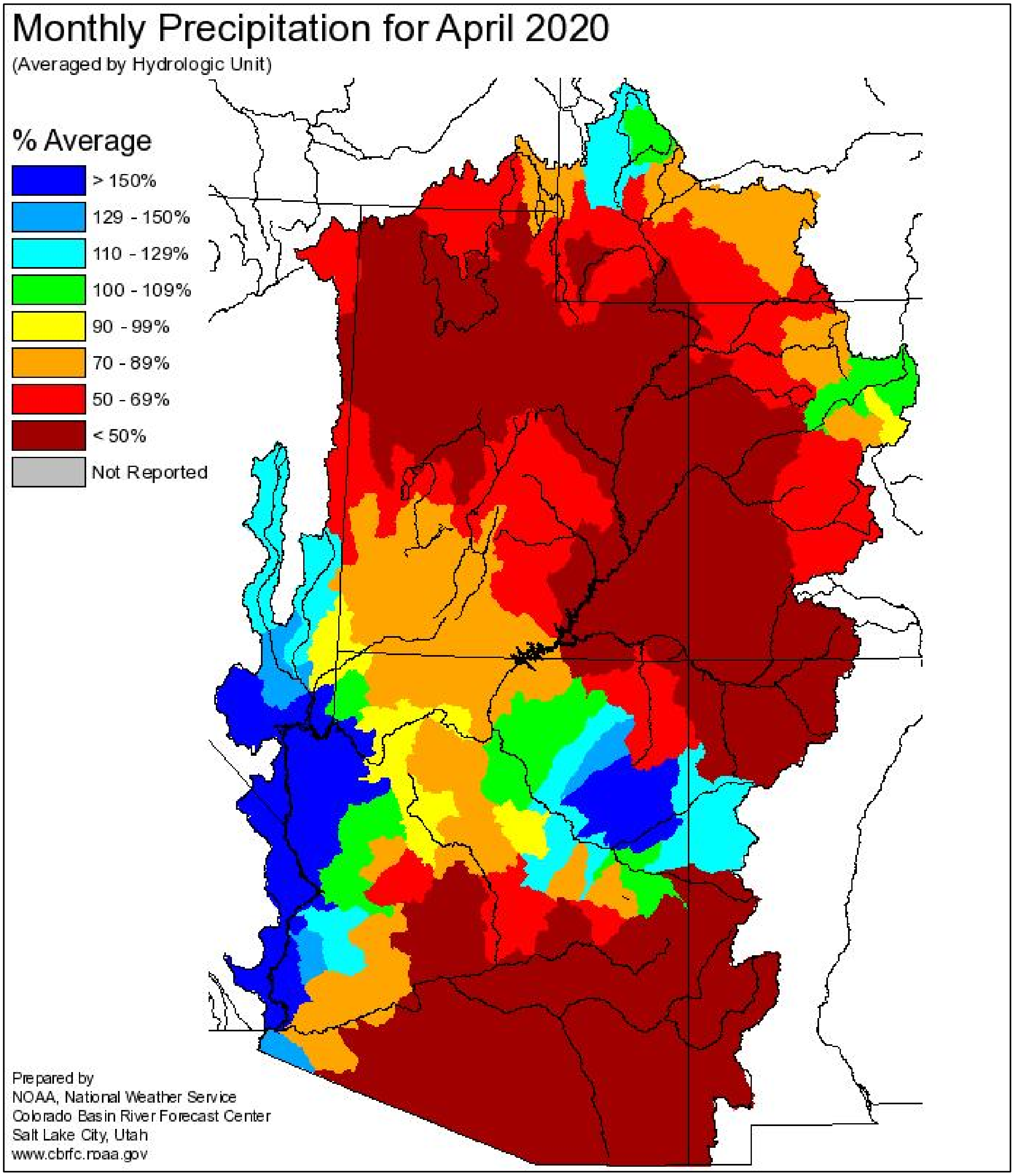

Figure 4.16 April 2020 precipitation, percent of normal

A vigorous cold front affected the Pacific Northwest and northern Rockies region on April 1st, bringing limited snowfall to roughly the northern half of Utah. Snowfall developed in central Utah overnight on the 1st into the 2nd behind the cold front, and seeding was initiated for the area from Sanpete County to near Piute County on the evening of April 1st. The front moved quickly through the area with snowfall totals of 1 inch to locally 3 inches, but in general this system only brought around 0.1 inches of water equivalent to the mountains of central Utah. Skyline observed a couple of icing cycles overnight, between about midnight and 0300 MDT, and Brian Head had some icing in the morning although not in association with any precipitation. Skies cleared early on April 2nd and seeding operations ended.

A well-defined closed low centered over California on April 8th expanded northeastward into southwestern portions of Utah on the night of April 8th-9th. Temperatures were initially warm with very high-based precipitating clouds, but in the core region of the low temperatures cooled to below -5°C overnight. Winds were generally from the south to southeast as this system moved into the area, which was favorable for seeding from some sites in far southern Utah to target the higher terrain of southwest and south-central Utah, including the high terrain around Brian Head which appeared the most favorable. On April 9th, the low retrograded (moved to the west) and dry conditions returned to Utah as the day went on, with seeding ending around midday. Brian Head recorded four icing cycles overnight (2100 – 0200 MDT) with a site temperature around -3°C to -5° C, with locally over 0.50 inches of precipitation in that area. Precipitation amounts were generally light and spotty elsewhere in the state.

A very large and cold trough covering much of Canada and the northern U.S. pushed a cold front into Utah from the north on April 15th-16th. Cold air advection and snow showers made conditions favorable for seeding for northern portions (mainly Sanpete County to affect northern portions of the Lower Basin extension area) overnight and through much of April 16th, with the 700 mb temperature dropping to near or below -5°C in that area. Seeding continued through much of April 16th as well to finish out the season, until precipitation ended later in the day. Skyline recorded a half dozen icing cycles overnight and up through late morning on April 16th, seen in Figure 4.17, with a site temperature between about -3°C to -6°C. SNOTEL data showed generally around 0.25 to 0.50 inches of water content. This marked the end of seeding operations for the season.

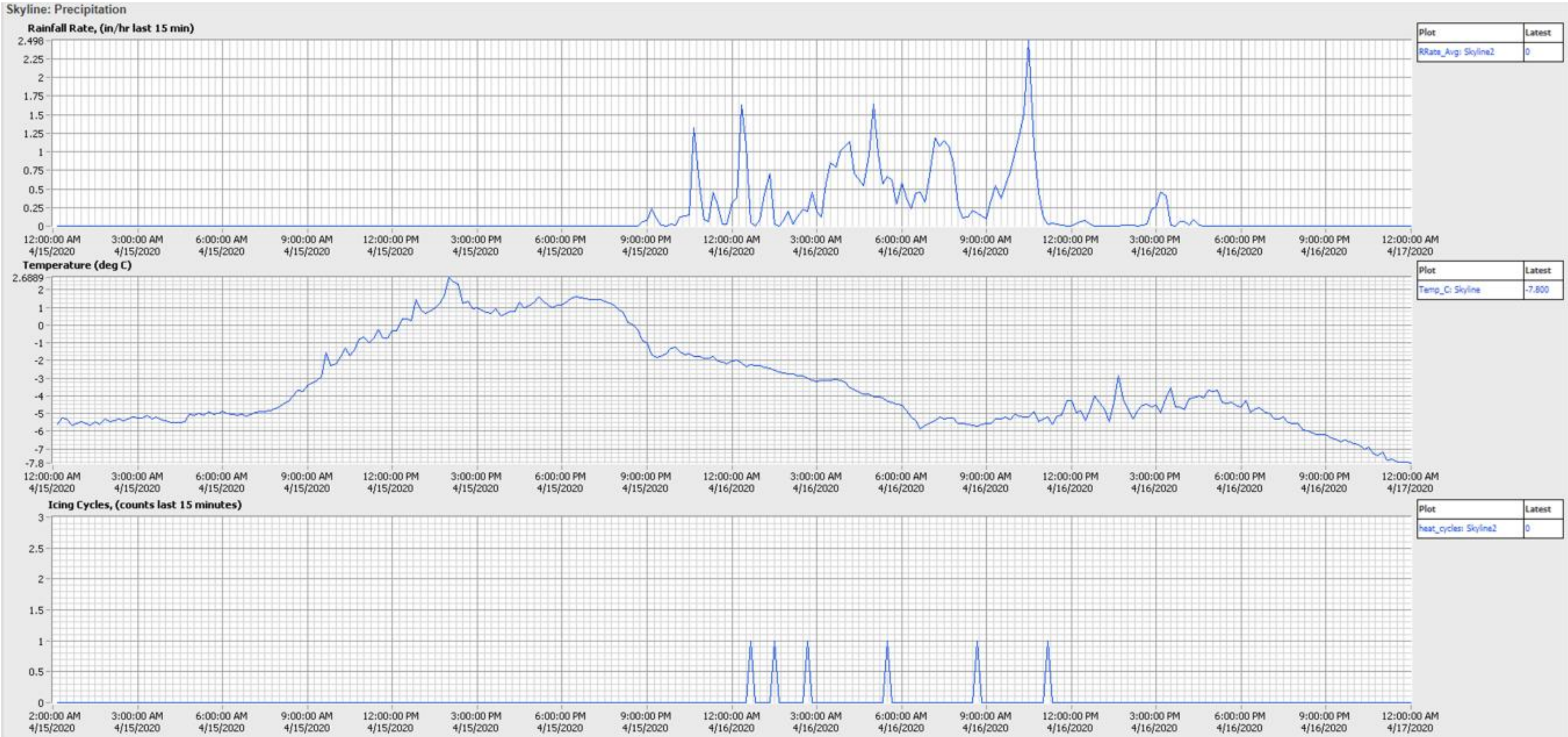

Figure 4.17 Skyline precipitation (upper panel), temperature (center), and icing cycles (lower panel) for April 15th – 16th. Icing was associated with snowfall and a temperature between about -3°C to -6°C at the site.

5.0 ASSESSMENTS OF SEEDING EFFECTS

5.1 Background

The seemingly simple issue of determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program is often a rather difficult task, however, and the results, especially single-season indications, should be viewed with appropriate caution. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area. 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, in weather modification, the most significant seeding results have been observed in wintertime seeding programs for snowpack augmentation in mountainous areas. The apparent increases due to seeding are generally less than 20% for individual seasons, and in the range of 5-15% for the long-term average. This section of the report summarizes statistical evaluations of the effects of the cloud seeding on the precipitation and snowpack within the higher elevations of this program's targeted areas. When expressed as percentages, the increases may not initially appear to be particularly high. However, when considering that these increases are area-wide averages covering thousands of square miles, the volume of the increased runoff is impressive.

NAWC has used a commonly employed evaluation technique since this seeding project was first evaluated following the 1978 water year. This technique, referred to as the target and control comparison, is based on evaluating the effects of seeding on a variable that would be affected by seeding (such as precipitation or snow water content). Records of the variable to be evaluated are acquired for an historical (non-seeded) period of sufficient duration, ideally 20 years or more. These records are partitioned into those that lie within the designated seeded target area of the project and those in appropriate control areas. Ideally the control sites are well-correlated with the target area sites but would be unaffected by the seeding. All the historical data, e.g., precipitation, in both the target and control areas are taken from a period that has not been subject to cloud seeding activities, since past seeding could affect the development of a relationship between the target and control areas. These two sets of data are analyzed mathematically to develop a regression equation which estimates (calculates) the most probable amount of natural target area precipitation, based on the amount of precipitation observed in the control area. This equation is then used during the seeded period to estimate what the target area precipitation should have been in the absence of cloud seeding. A comparison can then be made between the estimated natural target area precipitation and that which occurred during the seeded seasonal periods.

This target and control technique works well where a good statistical correlation can be found between the target and control area variables. Generally, the closer the control sites are to the seeding target area, the higher the correlation will be. Control sites which are too close to the target area, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, correlations of 0.90 or better are considered excellent and correlations around 0.85 are good. A correlation of 0.90 indicates that over 80 percent of the variance (random variability) in the historical data set is explained by the regression equation. Correlations less than about 0.80 are still acceptable, but it would likely take much longer (many more years of comparison) to attach any statistical significance to the apparent seeding results.

5.2 Evaluation Approach

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

There have been, and continue to be, multiple cloud seeding programs conducted in 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 most measurement sites in this part of the state have been subjected to contamination at some time by numerous historical and current seeding programs. This renders such sites of questionable value for use as control sites. The potential effects of other cloud seeding projects beyond (downwind) their intended target areas is a consideration especially when selecting control sites. Some earlier weather modification research programs have indicated that the precipitation can be affected in areas downwind of the intended target areas. Analyses of some of these programs have indicated increases in precipitation in these downwind areas out to distances of 50-100 miles. Thus, control sites for evaluation of the southern and central Utah seeding program are located in areas that are not expected to be significantly affected by any current or historical seeding operations.

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

Another consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control site may be rejected due to poor data quality, which usually manifests itself in terms of missing data. Fortunately, missing data (typically on a daily basis) are noted in the historical data base so that sites can be excluded from consideration if they have much missing data. We normally eliminate a site if it has significant amounts of missing data. If a significant measurement site move (more than a mile or change in elevation of 100-200 feet) is indicated in the station records, this may also be a factor. The double-mass plot, an engineering tool, will indicate any systematic changes in relationships between the two stations. If changes (shown as inflections in the slope of the line connecting the points) are significant, a site or sites may be excluded from further consideration.

Using the target-control comparison described above, the mathematical relationships for two variables (precipitation and snow water equivalent, or SWE) were determined between a group of sites in an unseeded area (the control group) and the sites in the seeded area (the target group). From these data, regression equations were developed whereby the amount of precipitation or SWE observed in the unseeded (control) area was used to estimate the amount of natural precipitation in the seeded (target) area. This estimated value is the amount of precipitation or SWE that would be expected in the target area without seeding. The difference between the estimated amount and the observed amount in the target area is the excess, which may be the result of the seeding.

Statistical tests have shown that such increases have very little statistical significance for an individual season, and usually fall within one standard deviation of the natural variability. However, an excess obtained by averaging the results of several seeded seasons is much more meaningful.

5.3 Evaluation of Precipitation in the Target Area

In past years several target areas have been evaluated to assess the efficacy of cloud seeding, by examining the precipitation observed at the gauges within the seeded targets. For the current water year, two target areas (see Figure 1.1) were again evaluated. An attempt has been made to consistently utilize the same groups of target and control sites from one season to the next, although there have been a few changes over the years as some sites were discontinued. The following describes the techniques that were used in selection of the target and control sites.

5.3.1 Precipitation Target Sites

The northernmost seeded target in the Central/Southern program is the East Tooele Target (ETT). That area contains the mountain watersheds of the Stansbury and Oquirrh Mountains, located in the eastern portions of Tooele County, south of the Great Salt Lake. Due to the scarcity of available target sites, this target group also includes a valley-level precipitation gauge (Tooele, just over 5,000 feet MSL), as well as a site (Vernon Creek) somewhat south of the official target areas. The locations of the three remaining precipitation gauges that were used in the evaluation for this target are listed in the target area portion of Appendix C and shown in Figure 5.1. The three target SNOTEL gauges are located in the Stansbury and Oquirrh Mountain ranges. The average elevation of the target gauges is 7,157 feet, MSL. Additional high elevation sites in the Stansbury and Oquirrh Mountain Ranges would be desirable in order to provide a more accurate evaluation of seeding effects in these target areas.

The Primary Target area is represented by 25 precipitation gauge sites. A few of the target site gauges are NWS cooperative observer sites, but the large majority consists of SNOTEL storage gauges. These sites are shown in Figure 5.2. The sites are located throughout the target area and should provide a representative data set for the evaluation. The average elevation for the target gauge array is about 8,800 feet MSL.

5.3.2 Precipitation Control Areas

The control site array for the precipitation evaluation of the Eastern Tooele Target seeding operation was the same group of control sites used in recent seasons' evaluations. The control group consists of six gauge sites, listed in Appendix C and shown in Figure 5.1. Four sites are located in eastern Nevada and two in northern Utah.

The precipitation evaluation control sites used for the Primary Target (PT) area evaluation are located in eastern Nevada and north central Arizona (bracketing the PT area on the northwest and southeast). The locations of these sites are shown in Figure 5.2.

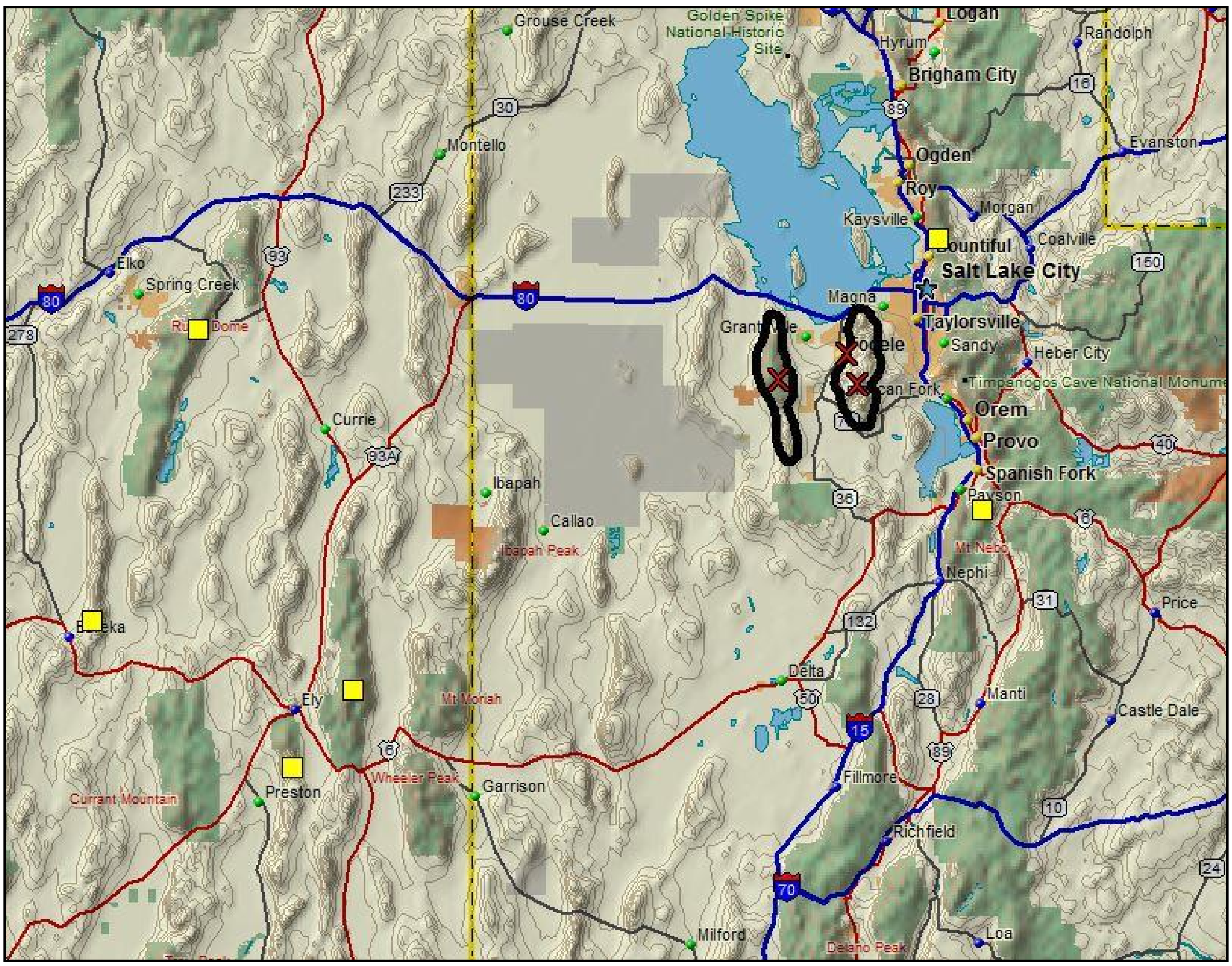

Figure 5.1 **Precipitation sites for Eastern Tooele target/control evaluation; control sites are depicted as squares and target sites with an X**

These sites have remained the same for a significant number of years, except for a few minor changes during the last few years, involving elimination or replacement of some valley co-op sites due to missing data or poor data quality. The remaining control group should be representative of storm systems that move across the target from northwest, west or southwesterly directions. Most of the sites in the control area are NRCS SNOTEL gauges at mountain locations.

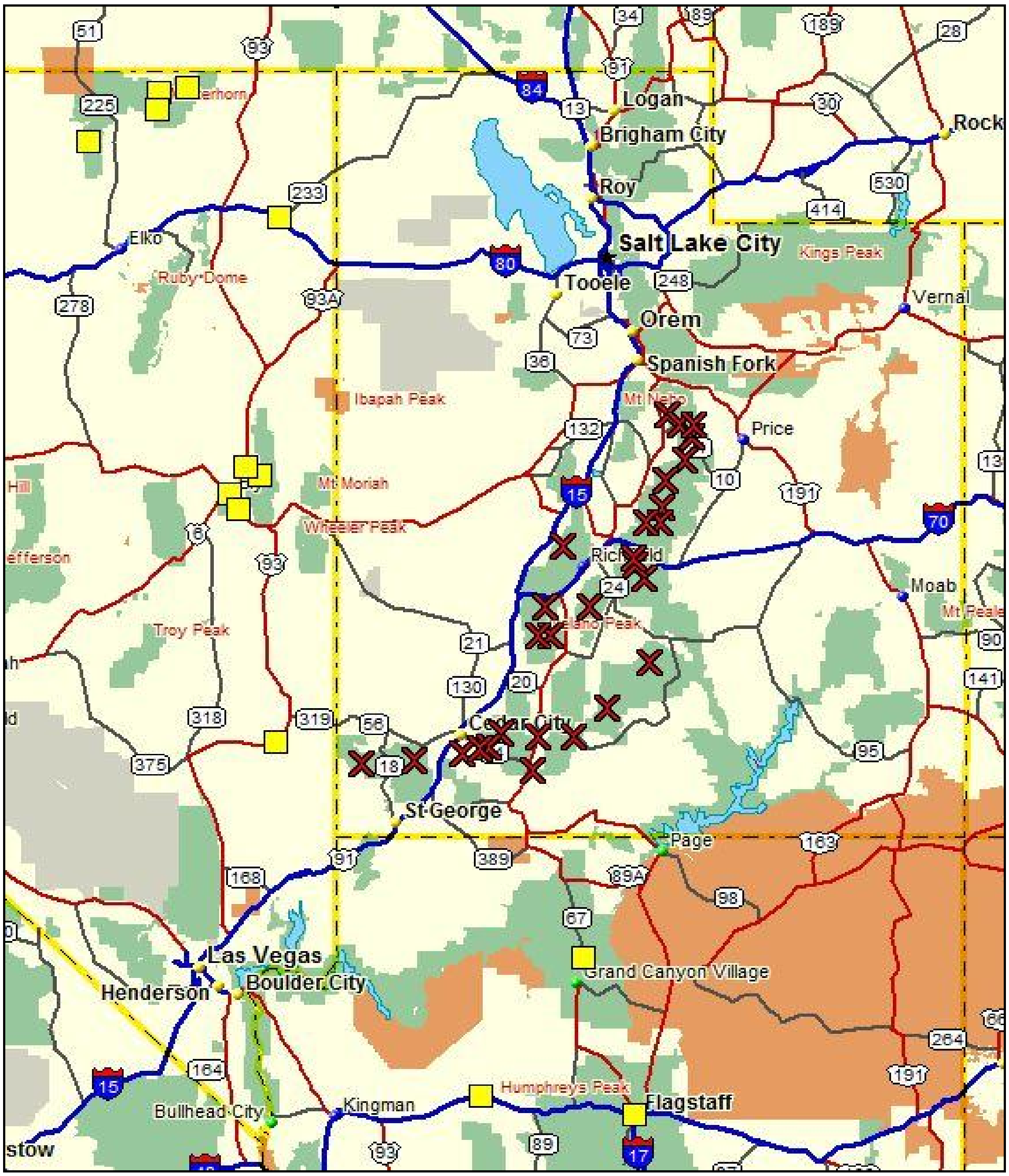

Figure 5.2 Precipitation target (X) and control (square) sites, primary target area

5.3.3 Precipitation Data Compilation

The evaluation was conducted for the December through March period, since this represents the period during which operational cloud seeding has been conducted in nearly all the seeded water years, although in some years the latter half of March has not been seeded. Precipitation data for some of the higher elevation target sites were obtained from storage gauge sites. Observations were taken at approximately monthly intervals before the conversion to the NRCS SNOTEL technology, which (at most sites) occurred in the early 1980's. With the advent of the NRCS SNOTEL system, data are available on a daily and even hourly basis, which eliminates some of the timing problems in the earlier data sets. Precipitation amounts for the December-March period were summed for each station, in the two target areas and their respective control areas. Averages were calculated for each of the groups for each individual four-month (December-March) season. The four-month averages for the historical (unseeded) seasons were then used to develop a linear regression equation for the target, which was in turn used to estimate the target area natural precipitation for the seeded period.

In the ETT, the historical (non-seeded) base period includes 28 non-seeded seasons (1957-75, 1983-88, and 1993-95). Seeded years in the ETT target include water years 1976-1982, 1989-1992, and 1996-2020 (36 seeded seasons). A reasonably good correlation between the control and target stations was established, with a correlation coefficient (r value) of 0.78. Target and control sites are listed in Appendix C. The control area sites are shown schematically on Figure 4.1 relative to the East Tooele Target area. Their average elevation is 8,348 feet MSL.

The historical period in the PT consists of an 18-year period (1957-73, and 1984). Seeded years began in 1974 in the PT and continued through 1983. Although seeding resumed in the southern portion of the PT in 1985, it was not until 1988 that a majority of the PT was being seeded again. Therefore, the 1985-87 period has been excluded from the evaluation, with target-wide seeding resuming in 1988 and continuing through the current water year. This provides a total of over 40 seeded seasons for evaluation. The regression analysis between the 12-site control area and the 25-site target area for the 18-year historical period (December-March, 1957-73, 1984 water years) provided an excellent correlation between the two groups. The correlation coefficient (r) is 0.96. This is a very strong correlation and should provide an accurate assessment of predicted natural precipitation in the target area during seeded seasons. The sites that make up the control and target areas are listed in Appendix C. The control area sites (denoted by squares) are shown schematically on Figure 4.2 relative to the Primary Target area. Their average elevation is 7,032 feet MSL.

The linear regression equation developed from the historical relationship between the control and target groups is of the following form:

$$Y_C = A(X_O) + B$$

where Y_C is the calculated average target area precipitation (inches) for a specific period (e.g., December-March), and X_O is the control average observed precipitation for the same period. The coefficients A and B, the slope and y intercept values from the historic regression equation are constants.

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

$$SE = R = (Y_O)/(Y_C)$$

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

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

$$SE = (Y_O - Y_C) / (Y_C \text{ x } 100)$$

The regression equations and the historical correlation coefficients for the two target areas are presented in Table 5-1. The stations which constitute each control/target group are listed in Appendix C.

5.3.4 Results of Precipitation Analyses

Table 5-2 provides the ratios of the observed average target area December-March precipitation to the calculated (from the regression equation described above) for the two target areas. A ratio equal to 1.0 would indicate no difference between the observed and predicted precipitation amounts. The difference between these values is also provided to show the average difference (inches) in precipitation during the seeded periods. Tables 5-3a and 5-3b list the results for each seeded season for the Eastern Tooele Target Area and Primary Target Area, respectively.

Table 5-1
Correlation coefficients, variances, and regression equations for precipitation evaluations

Target Group	Equation	Correlation Coefficient (r)	Variance (r^2)
Eastern Tooele (ETT)	$Y_C = 0.88(X_6) - 0.69$	0.78	0.61
Primary Target (PT)	$Y_C = 1.69(X_{12}) - 3.17$	0.96	0.91

Where:

Y_C = Average calculated precipitation for target (December - March)

X_6 = Average two state (NV/UT) control area observed precipitation for December - March for 6 sites

X_{12} = Average two state (AZ/NV) control area observed precipitation for December - March for 12 sites

Table 5-2
Precipitation evaluation results for the 2019-2020 December-March season and for all seeded seasons

Target Group	Seeded Period	Ratio	Increase (inches)
E. Tooele Co.	36 Seeded Water Years	1.12	1.3
	2020 Water Year	0.98	-0.2
Primary Target	43 Seeded Water Years	1.12	1.3
	2020 Water Year	0.98	-0.2

Where:

Ratio = Ratio of average observed target area precipitation to average calculated target area precipitation

Increase = Average difference (in inches) between observed and calculated precipitation at target gages

Table 5-3a
Eastern Tooele Co. (ETT) Target area
Summary of December - March precipitation evaluations

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1976	10.3	9.4	1.10	0.9
1977	6.6	6.9	0.96	-0.2
1978	20.7	16.3	1.27	4.4
1979	12.5	11.5	1.09	1.0
1980	19.6	15.8	1.24	3.8
1981	8.9	9.3	0.95	-0.5
1982	15.5	16.3	0.95	-0.8
1989	11.0	10.8	1.02	0.2
1990	9.8	7.7	1.27	2.1
1991	8.4	7.4	1.13	1.0
1992	7.4	7.4	1.01	0.1
1996	14.2	14.2	1.00	0.0
1997	15.0	12.9	1.16	2.1
1998	20.2	14.6	1.39	5.6
1999	9.3	8.8	1.05	0.5
2000	15.2	12.5	1.21	2.6
2001	9.4	8.3	1.12	1.0
2002	8.4	8.4	1.00	0.0
2003	8.7	7.6	1.14	1.1
2004	15.0	11.1	1.34	3.8
2005	15.4	13.4	1.15	2.0
2006	15.4	14.7	1.05	0.7
2007	9.9	8.3	1.19	1.6
2008	14.7	12.7	1.15	2.0
2009	13.6	13.2	1.03	0.4
2010	11.5	11.2	1.03	0.3
2011	16.6	14.9	1.11	1.6
2012	8.5	7.1	1.19	1.3
2013	9.5	8.3	1.15	1.2
2014	10.4	9.0	1.15	1.3
2015	6.2	6.0	1.03	0.2
2016	13.2	11.9	1.10	1.2
2017	18.8	16.8	1.12	2.0
2018	8.6	7.8	1.10	0.8
2019	17.3	15.5	1.11	1.8
2020	8.4	8.6	0.98	-0.2
Seeded Mean	**12.3**	**11.0**	**1.12**	**1.3**

Table 5-3b
Primary Target (PT) area
Summary of December - March precipitation evaluations

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1974	11.3	11.3	1.00	0.0
1975	12.8	12.1	1.06	0.7
1976	9.9	9.9	1.01	0.1
1977	6.4	4.6	1.40	1.8
1978	20.3	18.7	1.08	1.6
1979	16.3	14.5	1.12	1.8
1980	20.5	16.7	1.23	3.9
1981	9.3	8.0	1.16	1.3
1982	16.9	16.1	1.05	0.8
1983	17.5	15.0	1.17	2.5
1988	9.8	7.2	1.36	2.6
1989	10.2	10.3	0.99	-0.1
1990	9.1	7.8	1.17	1.3
1991	10.8	8.0	1.34	2.7
1992	10.2	7.6	1.34	2.6
1993	19.7	19.0	1.04	0.7
1994	8.7	6.5	1.35	2.3
1995	14.0	12.0	1.17	2.0
1996	12.9	12.2	1.05	0.7
1997	12.2	11.6	1.05	0.5
1998	14.4	12.6	1.14	1.8
1999	6.9	6.4	1.07	0.4
2000	12.4	10.8	1.15	1.7
2001	9.5	6.8	1.39	2.7
2002	6.2	6.7	0.92	-0.6
2003	9.6	6.6	1.45	3.0
2004	11.0	9.2	1.20	1.8
2005	15.9	14.2	1.13	1.8
2006	13.7	13.1	1.04	0.5
2007	7.2	7.4	0.98	-0.2
2008	15.1	11.7	1.28	3.3

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2009	13.1	11.6	1.13	1.5
2010	13.8	11.1	1.24	2.7
2011	16.6	14.3	1.16	2.3
2012	8.7	7.9	1.09	0.7
2013	9.2	8.9	1.04	0.4
2014	7.9	7.1	1.10	0.7
2015	8.4	7.7	1.09	0.7
2016	11.4	11.7	0.98	-0.3
2017	16.1	18.0	0.89	-2.0
2018	8.6	7.2	1.20	1.4
2019	15.7	15.3	1.03	0.4
2020	10.1	10.4	0.98	-0.2
Seeded Mean	12.1	10.8	1.12	1.3

5.3.4.1 Eastern Tooele Target Precipitation Results

Seeding began in the ETT in 1976 and continued through the 1982 water year. Seeding resumed in 1989 and continued through 1992. After a break in seeding during water years 1993-95, seeding resumed in the 1996 water year and has been conducted each year through the present. Thus, there are 36 seeded seasons and 28 non-seeded seasons in the regression period. For the single season evaluation, the regression equation resulted in an observed/predicted ratio of 0.98 as shown in these tables. While this number is not indicative of a single-season effect, it is important to remember that single-season evaluation results can vary significantly due to variability in precipitation patterns from one year to another, and, thus, a single-season result carries very little statistical significance. This variability primarily affects the results of the evaluation, not necessarily the actual effectiveness of the seeding. **During the 36 seeded seasons the observed precipitation within the target has averaged 12 percent greater than might have been expected from calculations based on the control precipitation averages. That increase is equal to an average additional 1.3 inches of water per seeded season.** Note that the December-March evaluations do not estimate any possible additional effects of seeding which was conducted outside this four-month core evaluation period (e.g., November 15th-30th, April 1st-15th).

Figure 5.3 is a scatterplot showing a comparison between the seeded and non-seeded data sets in the eastern Tooele County precipitation linear regression. The linear regression equation (e.g. best linear fit to the historical non-seeded data, shown in black) is represented by the black diagonal line. Note that the vast majority of the seeded season data (red dots) lie above the regression line, indicative of greater target area precipitation in seeded seasons than that predicted from the regression equation based upon control area precipitation.

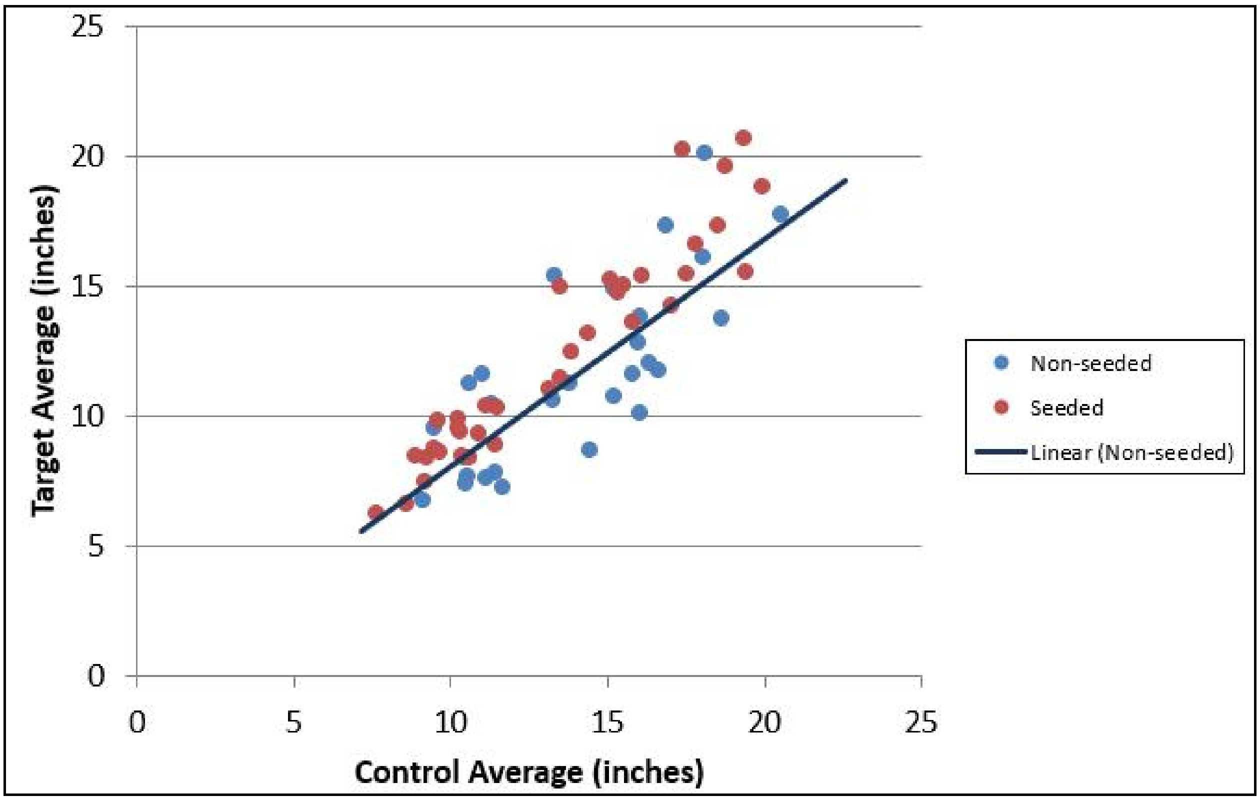

Figure 5.3 Scatterplot of historical non-seeded (blue) vs seeded (red) data points for the eastern Tooele County precipitation evaluation. The diagonal line represents the linear regression equation for the non-seeded period.

5.3.4.2 Primary Target Precipitation Results

Seeding was conducted in the target area beginning in the 1974 water year, continued until seeding was suspended in February 1983, and then discontinued entirely during water year 1984 because of excessively wet weather. However, seeding began again over portions of Washington County (mainly the Pine Valley Mountains) in 1985 and continued to spread northward in 1986 and 1987 into other parts of the target area. By

1988, seeding was again being conducted over essentially all of the previously seeded primary target area. The seeding program has continued to target most of the mountainous areas of central and southern Utah up through the current season. There have been 43 seeded seasons, excluding those when seeding was conducted over only a portion of the current target, and 18 seasons in the historical unseeded database. The 25 SNOTEL or cooperative observer sites located within the PT provide good coverage of the area targeted by cloud seeding. The high-density site coverage and distribution should ensure that the target area measurement sites are representative of the overall target area.

In the 2020 water year, the target/control precipitation evaluation results (from Table 5-2) yielded an observed/predicted ratio of 0.98 (similar to that in the Tooele County evaluation). As mentioned earlier, single-season results should be viewed with appropriate caution. **Over the 43 seeded years included in the long-term seeded record, 12 percent more precipitation has been observed (on average) than would have been expected from the control area-based predictions. This has provided an annual average excess of over 1.3 inches of water throughout the target area.** Statistical tests show the long-term average to be very meaningful (i.e., not the result of chance), even though individual-year results are not statistically significant. A one-tail significance test for the predicted vs. observed values (all seeded seasons) yielded a P value of 0.06 for this evaluation. This suggests only a 6% probability of the results of this one regression evaluation being due to chance. The December-March evaluations do not estimate any possible effects of seeding which was conducted outside of this four-month core evaluation period (e.g., November 15^{th} -30^{th} or during April).

Figure 5.4 is a scatterplot similar to Figure 5.3. Again, note that almost all of the seeded seasons are above the regression line indicating increases in precipitation. Appendix C contains the historical and seeded regression equation information for both target areas.

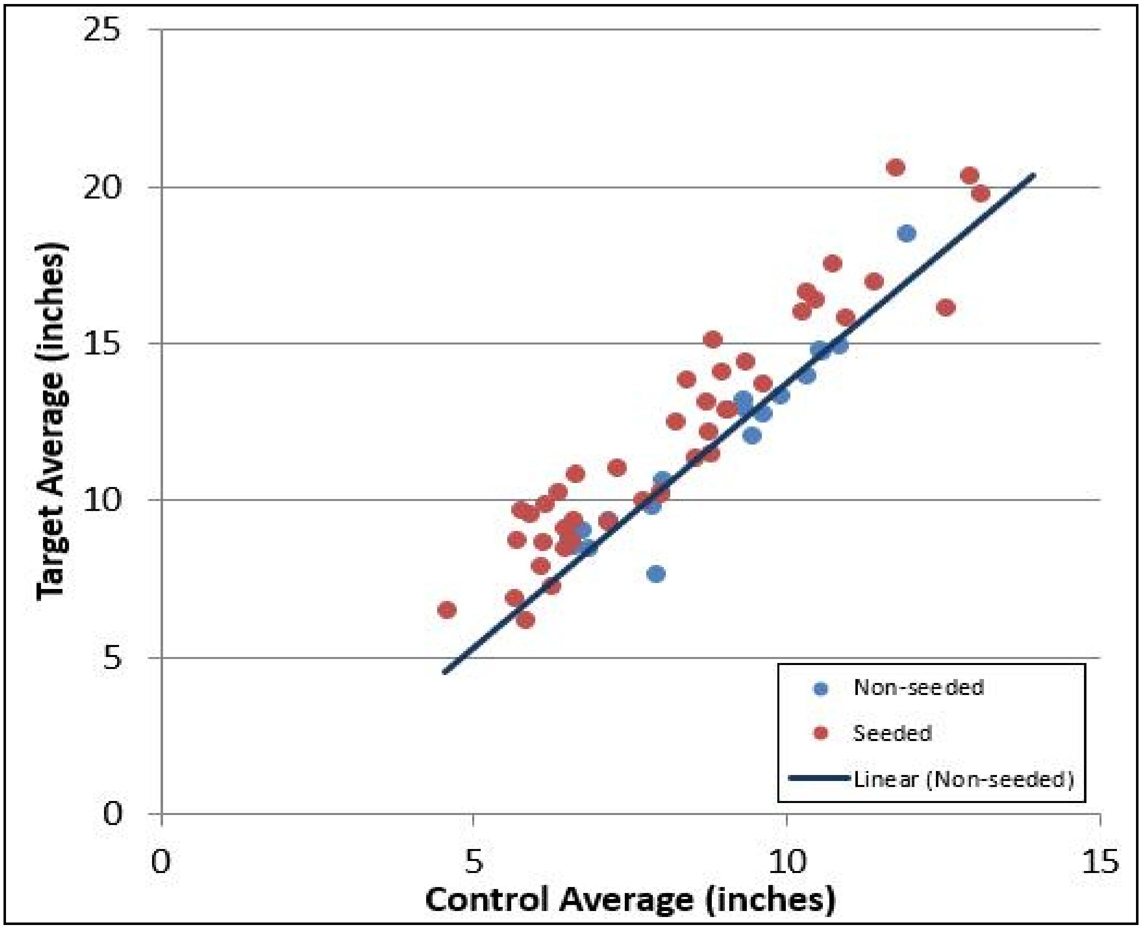

Figure 5.4 Scatterplot of historical non-seeded (blue) vs seeded (red) data points for the primary target precipitation evaluation. The diagonal line represents the linear regression equation for the non-seeded period.

5.4 Snow Water Equivalent (SWE) Evaluations

The procedure for evaluating the effect of cloud seeding on the snow water equivalent (SWE) as observed on April 1st was essentially the same as was done with the precipitation evaluations. In general, the control area snow sites have been drawn from approximately the same areas as were used in the precipitation evaluation, but they are limited to the availability of higher elevation sites which have significant SWE accumulation.

5.4.1 Target Area SWE Sites

Many of the same target sites (either snow course SNOTEL) that were used in the precipitation evaluation were also used in the SWE evaluation. The four target SWE site locations used for the ETT are shown in Figure 5.5 as X's. Two of these target sites are snow courses, while the other two are SNOTEL sites. The average elevation for the four target sites is 7,463 feet MSL.

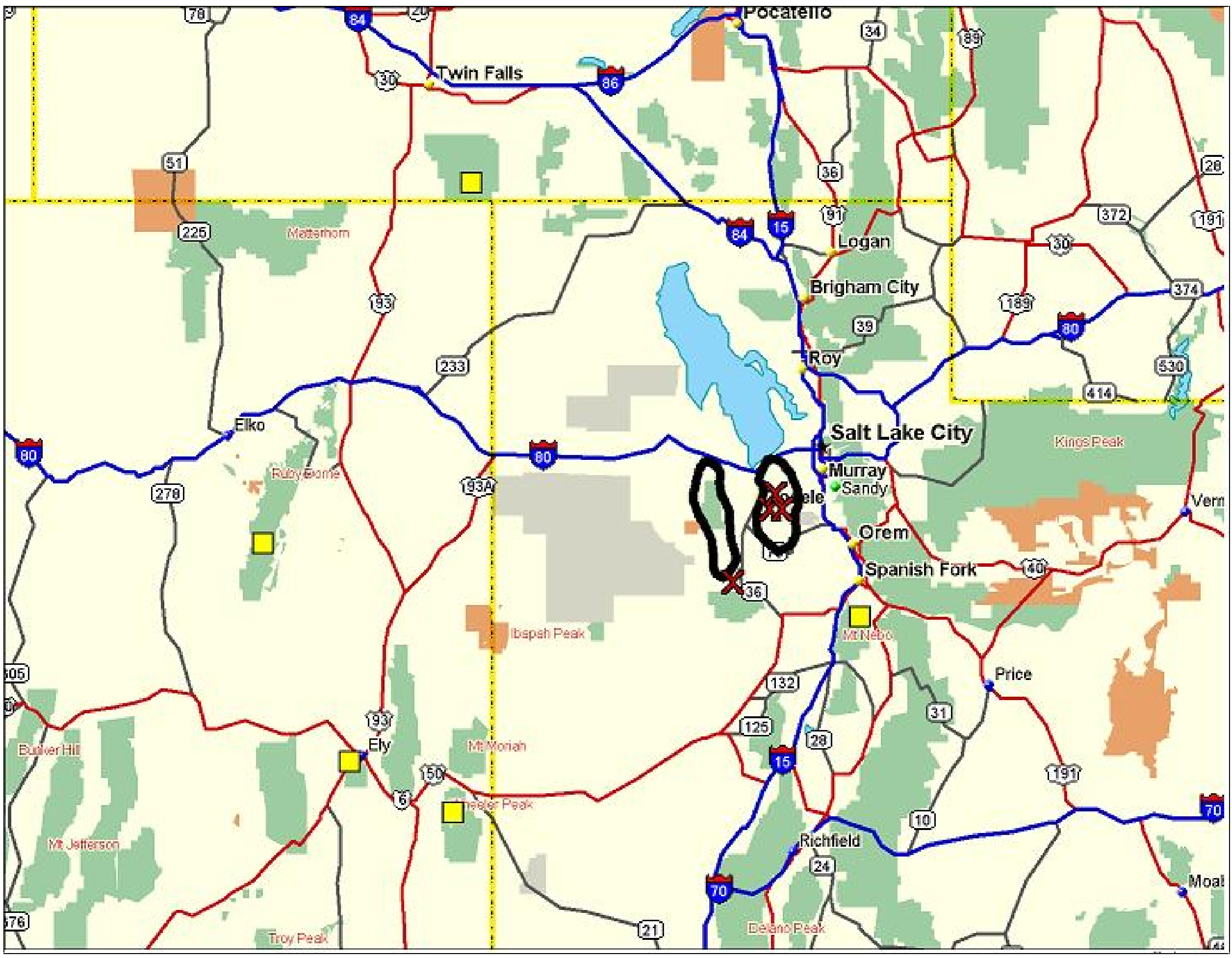

Figure 5.5 SWE sites for Eastern Tooele target/control evaluation (squares are control sites, X's are target sites)

A total of 30 target area SWE measuring sites were utilized in the Primary Target. Figure 5.6 shows target and control site locations. The average elevation for the target area sites is approximately 9,090 feet MSL. Actual site locations and elevations are listed in Appendix C for both target areas.

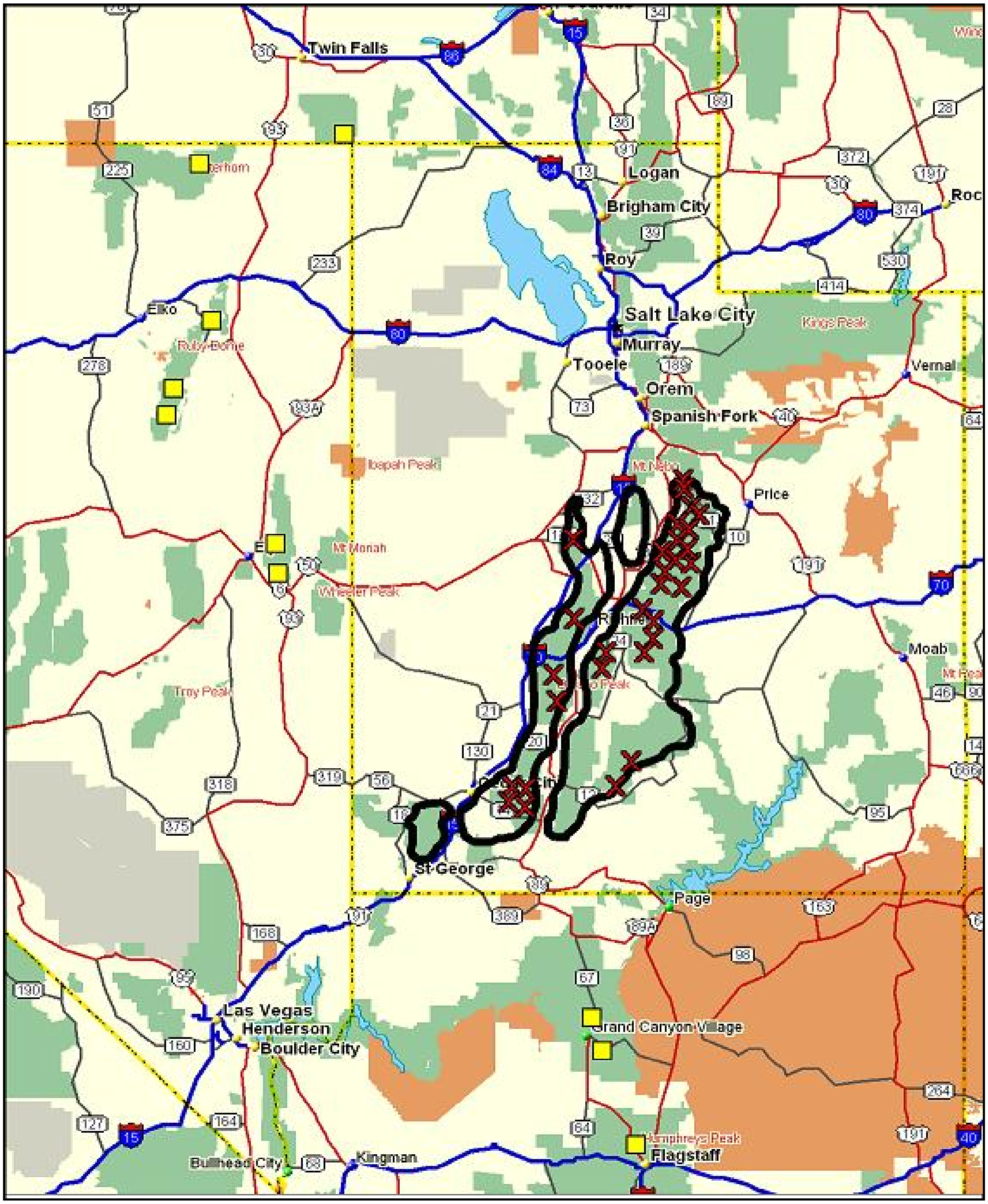

Figure 5.6 SWE sites for Primary Target evaluation (squares are control sites, X's are target sites)

5.4.2 Control Area SWE Sites

The selection of sites in the control group was determined primarily by their degree of correlation with each target area. Thus, control area sites (for the ETT and the PT) were selected individually from a large number of potential sites available in surrounding regions and assessed regarding their effects on the control vs. target group correlations.

The control group used in the SWE evaluation for the Eastern Tooele County target area (ETT) consists of five snow measurement sites. These sites extend from southern Idaho (one site) through eastern Nevada (three sites) into the Wasatch Mountains of Utah (one site southeast of the target area). The correlation coefficient (r) of 0.79 indicates a moderately good correlation between control and target areas and is slightly lower than that for the shorter regression period (0.82). Detailed information on the five SNOTEL/snow course sites utilized in this control is given in Appendix C, and the sites are shown in Figure 5.5. The average elevation of the control group about 8,050 feet MSL. Some data estimation was necessary for one of the sites (Vernon Creek) for the period prior to 1967, as SNOTEL/snow course data were unavailable. The estimation was based on data at two other target sites closest to Vernon Creek (Rocky Basin Settlement and Bevan's Cabin).

The Primary Target control group consists of ten SNOTEL/snow course sites located from southern Idaho southward through eastern Nevada into north-central Arizona. This control group provided a good correlation (r = 0.94) with the Primary Target, with a variance (r^2) of 0.88, indicating that 88% of the variability in the historical data used to predict the expected snowpack was explained in the regression equation. The locations of the ten sites used as the control area are listed in the control section of Appendix C and are shown as yellow squares in Figure 5.6. The average elevation of this control group is 8,800 feet MSL.

5.4.3 SWE Regression Equation Development

The procedure was essentially the same as was done for the precipitation evaluation, i.e., control and target area stations were selected and average values for each were determined from the historical SWE data. The regression equation for the Tooele County SWE evaluation is based on a 29-year non-seeded period (1956-75, 1983-88, and 1993-95). The regression period for the primary target is shorter, consisting of 18 years (1957-73, and 1984). The SWE regression equations developed for the ETT and PT areas, using historical SNOTEL and estimated SNOTEL April 1st snow water content data, are provided in Table 5-4.

Table 5-4
Correlation coefficients, variances and regression equations for SWE evaluation

Target Group	Equation	Corr Coeff (r)	Variance (r^2)
Eastern Tooele (ETT)	YC = 1.069(X5) – 0.81	0.77	0.59
Primary Target (PT)	YC = 1.04(X10) - 0.38	0.94	0.88

Where:

Y_C = Average calculated SWE for target (April 1st)

X_5 = Average three state (ID/NV/UT) control area SWE (April 1st) for 5 sites

X_{10} = Average three state (AZ/ID/NV) control area SWE (April 1st) for 10 sites

5.4.4 Results of Snow Water Content Analyses

The results of the snow water evaluations for current water year and the average for all seeded seasons for the ETT and PT are presented in Table 5-5. In some seasons, a large number of SNOTEL sites have experienced large decreases from peak SWE (10-50+%) prior to April 1st. For this reason, April 1st SWE evaluation results for water years 2007, 2012, 2015 and 2017 were excluded due to excessive pre-April 1st snow melt. Tables 5-6 and 5-7 list the results for each seeded season for the ETT and PT, respectively. Appendix D contains the historical and seeded year regression equation and evaluation result information for both target areas.

Table 5-5
Snow water content evaluation results for the 2019-2020 season, and for all seeded seasons

Target Group	Seeded Period	Ratio Y_o/Y_c	Increase Y_o-Y_c
Eastern Tooele (ETT)	32 water years*	1.10	1.4
	2020 water year	1.08	0.8
Primary Target (PT)	39 water years*	1.04	0.6
	2020 water year	1.21	2.4

* 2007, 2012, 2015 and 2017 results not included in long-term mean due to excessive pre-April 1st snow melt

Ratio = Ratio of average observed target area SWE to average calculated target area SWE

Increase = Average difference (in inches) between observed and calculated water content in snowpack at target gauges on April 1st

5.4.4.1 Eastern Tooele Results

Table 5-5 shows the Eastern Tooele target group snow water evaluation results for the current water year and for all seeded seasons. As in the SWE evaluation for the Primary Target area, the 2007, 2012, 2015 and 2017 (April 1) Tooele County SWE evaluation results are excluded from the long-term mean due to excessive pre-April 1st snowmelt. Table 5-6 shows individual year results for the ETT SWE evaluation. The long-term result of this evaluation, a ratio of 1.10 equivalent to a 10% increase, is also close to the 1.12 ratio for the ETT precipitation evaluation (see Table 5-2 for comparison). The difference in observed versus calculated snow water (in inches of water) showed an average of about 1.3 inches more water observed than calculated per year for both (snow and precipitation) analyses in the Tooele County portion of the program. Results for the current season are also shown (a ratio of 1.08 which suggests an 8% increase), although it should again be emphasized that single-season results carry very little statistical significance.

Table 5-6
Eastern Tooele Co. (ETT) Target area, April 1st snow water content evaluation

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1976	15.6	16.0	0.98	-0.4
1977	9.3	5.8	1.59	3.5
1978	21.1	17.8	1.18	3.3
1979	18.0	19.4	0.93	-1.4
1980	24.4	19.5	1.25	4.8
1981	12.5	9.2	1.36	3.3
1982	19.6	22.1	0.89	-2.5
1989	9.9	14.1	0.70	-4.2
1990	12.4	10.7	1.16	1.7
1991	10.5	10.1	1.05	0.5
1992	10.3	8.5	1.21	1.8
1996	12.8	14.7	0.87	-1.9
1997	17.9	15.0	1.19	2.9
1998	23.4	15.0	1.56	8.4
1999	8.8	10.0	0.88	-1.2
2000	15.9	11.2	1.42	4.7
2001	11.4	8.5	1.35	3.0
2002	11.0	11.2	0.98	-0.2
2003	9.6	8.3	1.16	1.3
2004	15.0	10.1	1.49	4.9
2005	20.2	18.5	1.09	1.7
2006	16.3	17.0	0.96	-0.6
2007*	7.2	6.4	1.11	0.7
2008	17.5	14.4	1.21	3.1
2009	13.9	12.6	1.10	1.2
2010	13.0	12.2	1.06	0.8
2011	21.9	16.3	1.34	5.5
2012*	7.2	7.9	0.91	-0.7
2013	10.0	7.7	1.30	2.3
2014	8.3	9.9	0.83	-1.7
2015*	1.5	3.6	0.43	-2.0
2016	12.0	13.8	0.87	-1.8
2017*	13.8	13.0	1.06	0.8

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2018	5.3	8.1	0.66	-2.8
2019	21.4	20.0	1.07	1.4
2020	11.5	10.7	1.08	0.8
Seeded Mean	14.4	13.1	1.10	1.3

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

5.4.4.2 Primary Target Results

Table 5-7 shows the individual and combined season results of the April 1st SWE evaluation for the Primary Target areas. As discussed in the previous section, the 2007, 2012, 2015 and 2017 April 1st SWE evaluation results are excluded from the long-term mean due to excessive early season snowmelt in those seasons. The data for the combined seeded seasons included in the evaluation indicates a ratio of observed to calculated snow water of 1.04. This ratio (1.04) is much less than the ratio of 1.12 for the precipitation evaluation for this primary target group, and the resulting statistical significance (one-tail P value of 0.29) is less as well. Indications of excess snow water content provided by the SWE evaluation are also less than in the precipitation results, with an average of 0.6 inches per year in the snow water analysis and 1.3 inches per year indicated by the precipitation evaluation. These differences are discussed in section 5.7.

Table 5-7
Primary Target (PT) area
April 1st snow water content evaluation

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1974	15.6	14.0	1.11	1.6
1975	17.3	18.3	0.95	-1.0
1976	12.9	12.8	1.01	0.2
1977	8.2	8.0	1.02	0.2
1978	21.8	18.9	1.15	2.9

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1979	21.4	18.2	1.17	3.2
1980	23.6	19.6	1.20	4.0
1981	10.2	9.6	1.06	0.6
1982	20.5	20.7	0.99	-0.2
1983	26.0	23.6	1.10	2.4
1988	13.1	10.5	1.25	2.7
1989	11.3	14.6	0.77	-3.4
1990	10.5	9.1	1.16	1.4
1991	12.8	12.3	1.04	0.5
1992	12.1	11.7	1.04	0.4
1993	21.3	20.4	1.04	0.9
1994	10.8	9.3	1.17	1.6
1995	16.6	18.0	0.92	-1.4
1996	14.6	13.8	1.06	0.8
1997	15.1	15.7	0.96	-0.6
1998	16.7	17.4	0.96	-0.7
1999	8.1	10.3	0.79	-2.2
2000	13.7	12.9	1.06	0.8
2001	11.3	10.8	1.04	0.5
2002	9.6	10.4	0.92	-0.8
2003	12.1	9.5	1.28	2.6
2004	10.2	9.2	1.11	1.0
2005	20.1	21.1	0.95	-1.0
2006	17.4	16.9	1.03	0.5
2007*	6.8	7.8	0.87	-1.0
2008	16.1	15.2	1.06	0.8
2009	12.7	13.0	0.98	-0.2
2010	15.1	14.8	1.02	0.3
2011	20.1	16.2	1.24	3.9
2012*	7.9	7.1	1.11	0.8
2013	9.3	8.8	1.06	0.5

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2014	9.9	9.4	1.05	0.5
2015*	6.1	4.7	1.28	1.3
2016	12.8	14.4	0.89	-1.5
2017*	13.9	16.6	0.84	-2.7
2018	7.9	8.1	0.97	-0.2
2019	19.5	18.9	1.03	0.6
2020	14.0	11.6	1.21	2.4
Seeded Mean	14.7	14.0	1.04	0.6

* Results not included in long-term average due to excessive early-season snowmelt

5.5 Multiple Linear Regression Analyses

A variation of the linear regression technique is a multiple linear regression. In the linear regression averages of the control site data and target site data are used in development of the equation. In a multiple linear regression typically an average of all the target site data is correlated with each individual control site resulting in an equation with a number of terms depending upon the number of control sites. Past work with multiple linear regression evaluations highlighted some potential problems with this type of evaluation under certain circumstances. For example, a multiple linear regression equation containing independent control variables (e.g. single control sites) that are too similar to each other may yield an unrealistic regression equation. Such an equation typically produces highly variable results (that is, very high and/or very low individual season observed/predicted ratios) when applied to seeded season data.

One way to reduce or eliminate problems with the multiple regression analysis is to group control sites into 2 (or more) sets, with each set containing an average of a grouping of control sites. Ideally, control sites with similar characteristics (such as those at a higher latitude in comparison to much of the target area, and those at a lower latitude) can be grouped for this purpose, allowing the multiple linear regression equation to distinguish between the two groups in a meaningful way. Testing the standard deviation of the resulting individual seeded year ratios provides a useful comparison between a linear and corresponding multiple linear regression technique. Although a multiple linear regression equation containing the same control sites will typically have a better correlation (higher r-value) than the linear, ideally the resulting individual year observed/predicted ratios should have less variability (lower standard deviation) as well. This indicates that the multiple linear regression equation is helping to reduce some of the natural variability or "noise" inherent in the target /control relationship.

Most of the multiple linear regression equations developed for the southern/central Utah seeding program produced much more variable individual seeded season results than did the linear regression equations, and so the results from most of these have not been considered very reliable for this program. However, for the primary target area, it was found that a multiple linear SWE regression equation containing two control sets (one an average of the five northern-most control sites, and the other an average of the five southern-most sites) reduced the variability in the seeded season results slightly. For the combination of all seeded seasons, this multiple linear SWE regression produced an observed/predicted ratio of 1.03 (similar to the 1.04 long-term result for the linear regression equation).

5.6 <u>Double Mass Plots</u>

A double mass plot is an engineering tool designed to display data in a visual format in which it can readily be seen if there has been a change in the relationship between two variables. NAWC has applied this technique to the central/southern Utah cloud seeding program. Figures 5.7 and 5.8 provide plots of the data used by NAWC in target area evaluations of December – March precipitation, for the Primary Target and Eastern Tooele County Target areas. Target and control area-average seasonal values for both the historical (not-seeded) and the seeded periods are plotted on the figures. The December – March precipitation data are used in these plots since these data best represent the seeded season. The plotted values are cumulative; each new season is added to the sum of all of the previous seasons. In each figure, a line has been drawn through the points during the not-seeded base period. The plots show stable linear relationships prior to the beginning of cloud seeding. For comparison with the seeded period, the line describing the not-seeded period is extended at a constant slope through the seeded period. The Eastern Tooele County plot (Fig. 5.8) is more complex since there were two non-seeded intervals (from 1983-88 and 1993-95) even after the beginning of initial seeding operations in 1976. However, the line in this plot is drawn to fit the pre-seeding historical period of 1957-1975.

Figures 5.7 and 5.8 show a distinct change in the relationship between the target and control areas (a sustained change in the slope of the line representing the seeded seasons) that begins at approximately the same time as the start of the cloud seeding programs in the mid to late 1970s. Beginning at/near this time the plots in each case show generally greater precipitation in the target area compared to the control area. NAWC believes that this demonstrates evidence of a consistent positive seeding effect. A separate line could be drawn through the data points since seeding began in each case. Such a line would also have a fairly constant slope, departing from the slope of the line describing the not-seeded base period.

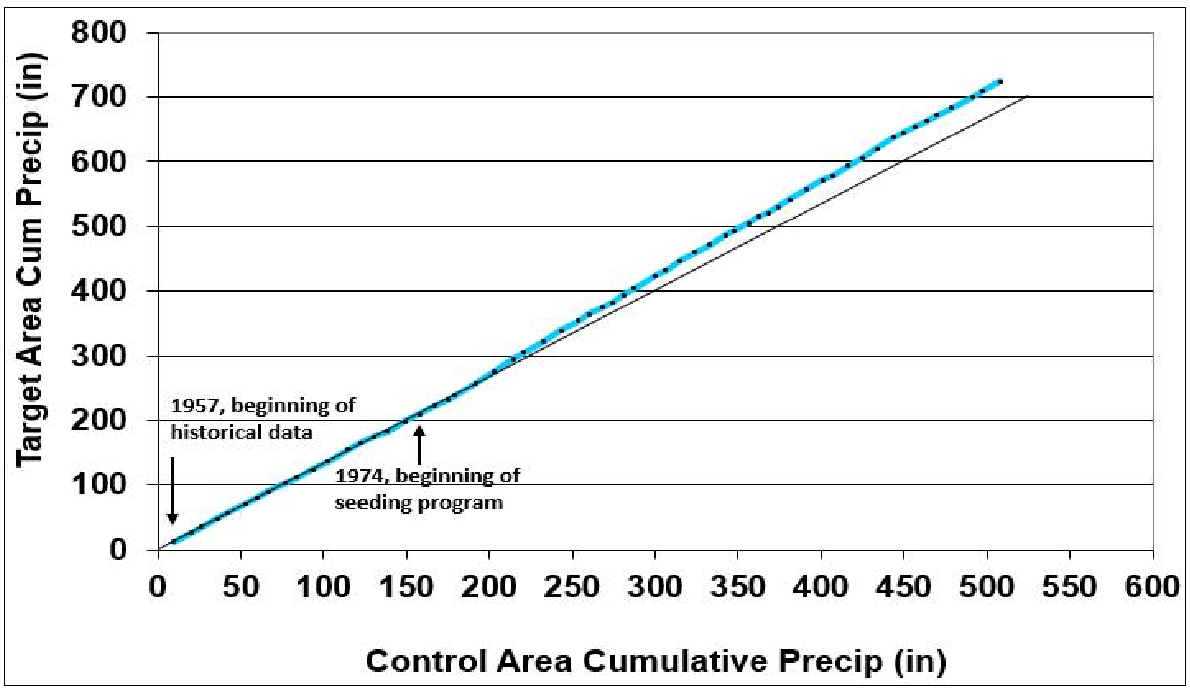

Figure 5.7 Double-Mass plot for Primary Target; all seasons shown after 1974 in this plot were seeded, and all the seasons plotted previous to this were not seeded

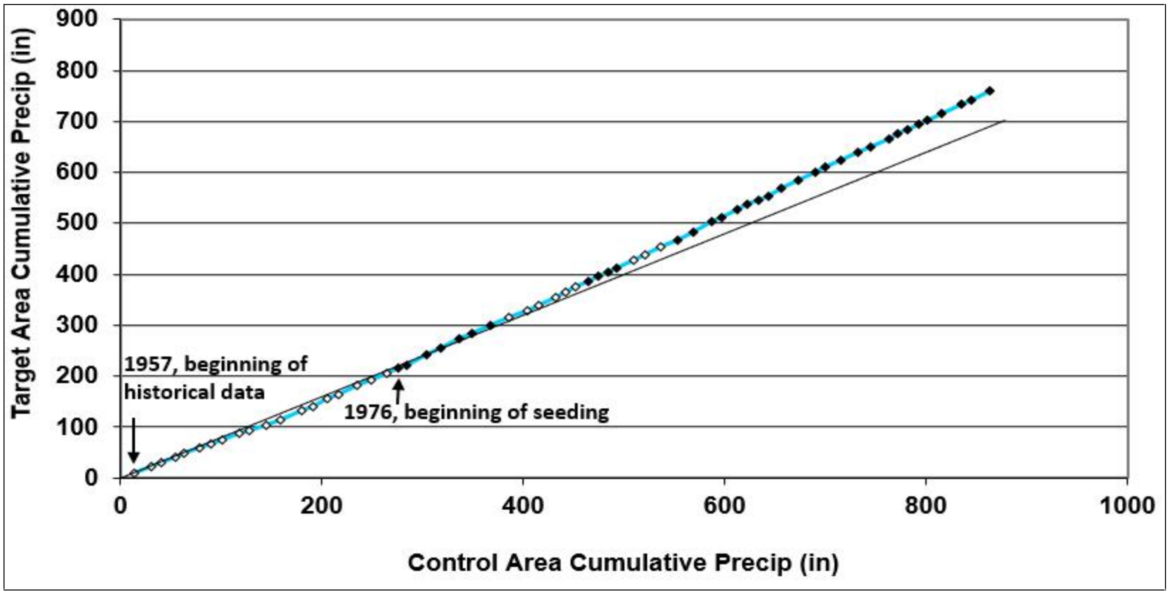

Figure 5.8 Double-Mass plot for Eastern Tooele County Target; smaller data points denote non-seeded seasons, and larger, darker points are the seeded seasons

5.7 Summary of Evaluation Results

Table 5-8 summarizes the results of the seeding evaluations, both for the ETT and PT target areas, for precipitation and SWE. Combined results of all seeded season evaluations suggest an approximate 10-12% increase in precipitation/snow water for the ETT, with a range of 3-12% increases indicated for the PT in the various linear and multiple linear regression evaluations.

Table 5-8
Summary of ratios from precipitation and SWE evaluations

	2020 Water Year	Long-term Average
ETT Precipitation Linear	0.98	1.12
ETT SWE Linear	1.08	1.10
PT Precipitation Linear	0.98	1.12
PT SWE Linear	1.21	1.04

The reader will note the significant differences in results between the precipitation and SWE analyses, which have persisted even though the target and control groups have had minor adjustments over time (usually due to loss of site data availability), and various combination of sites have been examined in regression equations. One factor involved in this difference is that SWE accumulation usually begins before the seeded portion of the season, and therefore the seeding effects on snow water content are diluted by the early season non-seeded period. The seeding program in some years has ended by mid-March, making this a potential factor in the spring as well. Also, it was determined that the change in SWE measurement methods (the advent of SNOTEL) which occurred in about 1980, and the ensuing data adjustments applied by NRCS, may result in an underestimate of seeding effects in the SWE evaluation for the Primary Target, as was discussed in further detail in some past reports. Based on these considerations, it is concluded that the estimates of cloud seeding effectiveness for the Primary Target for December through March precipitation are more reliable than those based upon April 1st snow water content.

As a side note, the December-March precipitation evaluations do not estimate any possible effects of seeding which was conducted outside of this four-month core evaluation period (e.g., November 15-30 or during April). NAWC performed an analysis of the potential increases in streamflow from these extension periods (Griffith et al., 2010) at the request of a Lower Basin States representative. This analysis provided estimates of **average** March – July increases in streamflow to Lake Powell (20,271 acre-feet) and to Lake Mead (8,331 acre-feet). The estimated cost per acre-foot of the calculated average increases were $1.22 per acre-foot for inflow to Lake Powell and $1.81 per acre-foot for inflow to Lake Mead.

6.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 <u>Summary</u>

Snowpack and precipitation was generally near normal in central and southern Utah during the 2019-2020 winter season, with somewhat below normal values in portions of west-central Utah and above normal values in the far southern portion of the state. As of April 1st, 2020, snowpack water equivalent ranged from 97% to 138% of the median in the southern and central Utah Basins, with basin average water year precipitation amounts from 80% to 101% of the mean. Figure 6.1 shows the April 15th, 2020 USDA snowpack basin percentage map.

A total of 18 storm events were seeded during the regular contract period, and 9 additional events were seeded during the spring extension period. There were no seeding opportunities during the November 1st-15th portion of the Lower Basin States extension. In all, there were three storm events seeded in November, four events in December, seven in January, two in February, eight in March, and three in April. For the regular contract period, a cumulative 3,602.25 generator hours were utilized. For the Lower Basin extension, there was an additional 1,376.75 generator hours of seeding conducted.

Precipitation linear regression evaluations for the December-March period this season yielded a ratio of 0.98 for both the Eastern Tooele Target (ETT) area for the Primary Target (PT) area. **<u>Long-term</u> ratios of 1.12 were obtained for both ETT and PT precipitation evaluations, based on 36 seeded seasons in the ETT and 43 seeded seasons in the PT. These ratios suggest about a 12% average precipitation increase during the seeded seasons, which may be attributed to seeding operations. A one-tail statistical test resulted in a P value of 0.06 for the PT precipitation evaluation suggests only a 6% probability of this result being due to chance. The 12% indicated precipitation increase for the ETT and PT precipitation evaluations is equivalent to approximately 1.3 inches of additional water per season for the ETT and PT, respectively.**

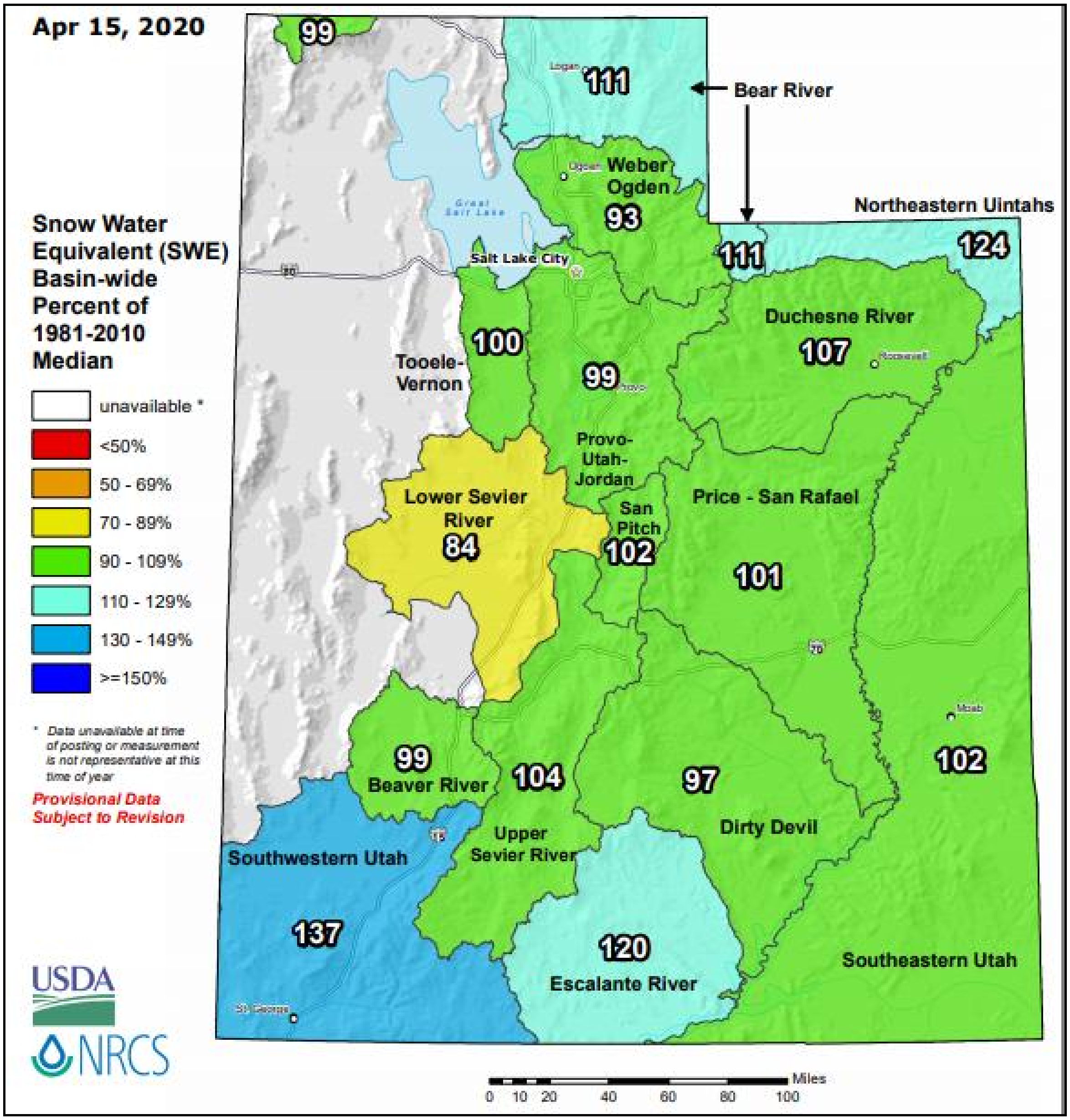

Figure 6.1 Western U.S. Percent of Median April 15th, 2020 Snow Water Content

Snowpack evaluations for the current season yielded ratios of 1.08 (ETT) and 1.21 (PT). Long-term results of the snowpack evaluations are 1.10 and 1.04 for the ETT and PT, based on 32 and 39 seeded seasons, respectively. As described in previous reports and in Section 5 of this season's report, the 2007, 2012, 2015 and 2017 snowpack data were excluded due to abnormal early season snowmelt in these years**.** Due to some of the potential problems regarding snowpack observations (as discussed in Section 5.5), we believe that the multi-season December through March precipitation evaluations are likely more representative for the Primary Target area than are the snowpack evaluations.

As stated previously, the seasonal average increases indicated by the December through March precipitation evaluation in the PT is an average of 1.3 inches of additional precipitation over the entire seeded PT area and an average of 1.3 inches for the ETT. These values are probably underestimates of the actual seeding effect since they are specific to the December through March period, seeding in many winter seasons has been conducted outside of this period (e.g., during the month of April). For the PT, no attempt was made to evaluate the effects of seeding specific to the extension periods made possible through funding provided by the three Lower Colorado River Basin States, although similar increases (percentage-wise) would be expected as those which have been indicated for the core program. NAWC's experience has been that short time periods (e.g., one month) provide lower correlations than in a seasonal evaluation, and that evaluation of short periods (such as a one month period) is extremely difficult unless the effects of seeding are very large. Fortunately, we now have enough seeded seasons to result in a high level of confidence in the indications of the degree of increases in December through March target area precipitation.

6.2 <u>Conclusions</u>

Winter season cloud seeding in Utah, the nation's second-driest state, offers a viable method of increasing water supplies at very attractive benefit/cost ratios. The operational seeding program conducted over the central and southern Utah mountain watersheds during over 42 winter seasons appears to have consistently provided additional precipitation.

The value of the cloud seeding program was clearly demonstrated in an independent study performed by the Utah Division of Water Resources entitled "Utah Cloud Seeding Program, Increased Runoff/Cost Analyses" (Stauffer and Williams, 2000). The report used estimated increases of April 1st water content from an earlier NAWC annual project report (similar to this one), but with verification of those numbers by the Division, to estimate increases in streamflow due to cloud seeding. After an update (Hasenyager, et al., 2012), the results from this report for the various seeding target areas in Utah are summarized in Table 6-1. This report estimated an average annual increase in runoff due to cloud seeding in Utah of 181,700 acre-feet, which is an increase of 5.7 percent. The resulting cost per acre-foot for the additional water was $2.27 based upon the 2009-2010 total project costs.

It is concluded, based on the numerous statistical evaluations of this program and similar seeding programs in the western U.S., that winter season weather modification in Utah is a viable, cost-effective method for enhancing water supplies. The cost to produce the additional water is comparatively low and the attendant program benefit/cost ratio very attractive.

Table 6-1
Increased Runoff and Cost for the Utah Cloud Seeding Projects

Project	Increased Runoff (acre-feet)	Cost ($)	Cost ($/acre-foot)
Northern Utah	56,300	87,097	1.55
Central and Southern	72,089	188,768	2.62
Western Uintas	17,122	45,703	2.67
High Uintas	36,190	90,432	2.50
Total	181,700	412,000	2.27

6.3 Recommendations

It is recommended that the winter seeding programs over the mountainous portions of central and southern Utah be continued. Routine application of weather modification technology each year can help stabilize and increase water supplies, both with surface and underground storage. Commitment to conduct a program each winter provides stability and acceptance by funding agencies and the general public. The program is designed so that it can be temporarily suspended or terminated during a given winter season, should snowpack accumulate to the point where additional water may not be beneficial.

Other reasons to conduct the program in an ongoing fashion, rather than only during drier-than-normal winters include:

1) it is very difficult to predict a wet or dry season in advance.
2) a season could start out wet, but then turn dry. In this case the earlier seeding opportunities in the wet period would be missed.
3) drier seasons, by definition, will have fewer seeding opportunities, which means the total water increase due to seeding will be less.
4) seeding in normal and above-normal water years will provide additional water supplies (surface and underground carryover) for use in dry periods.

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APPENDIX A

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	186.54	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 the Park Valley	5,733	George Creek	17.84	187.75	18.32	143.81	28.93	163.43	34.61	153.77	1
	USGS 10172952	Howell Canyon, Idaho	28.71	279.96	38	223.24	44.59	205.98	50.46	191.65	2
		Average	**23.30**	**233.90**	**28.20**	**183.60**	**36.80**	**184.70**	**42.60**	**172.70**	
2. Western & High Uintah	166,861	Lily Lake	11.38	202.70	16.40	194.06	17.69	147.37	28.93	139.19	1
Bear River near Utah - Wyoming state line	USGS 10011500	Trial Lake	20.07	206.54	26.56	182.26	33.68	173.94	38.49	162.05	2
		Hayden Fork	12.41	197.65	17.06	175.83	21.03	160.98	20.90	146.02	3
		Average	**14.60**	**202.30**	**20.00**	**184.10**	**24.10**	**160.80**	**29.40**	**149.10**	
Duchesne near Tabiona	140,976	Strawberry Divide	6.92	239.23	10.87	199.25	26.77	178.78	29.75	179.05	1
	USGS 09277500	Daniels-strawberry	16.07	248.12	21.59	202.44	27.82	190.54	29.89	192.75	2
		Smith Morehouse	10.61	196.64	14.95	172.41	18.82	158.83	22.22	168.26	3
		Rock Creek	8.76	230.02	12.31	219.65	15.88	205.68	16.41	209.06	4
		Average	**10.60**	**228.50**	**14.90**	**198.50**	**22.30**	**183.50**	**24.60**	**187.30**	
Provo near woodland	183,845	Trial Lake	22.98	236.53	27.78	190.63	35.23	181.59	31.44	132.39	1
	USGS 09277500	Beaver Divide	10.29	210.39	14.11	179.49	17.45	170.83	20.18	200.3	2
		Average	**16.70**	**223.50**	**20.90**	**185.10**	**26.30**	**176.20**	**25.80**	**166.40**	
3. Central & Southern	120,473	Castle Valley	12.23	244.05	16.96	203.04	22.22	187.68	26.30	180.00	1
Sevier near Hatch	USGS 10174500	Harris Flat	8.71	298.76	15.25	273.59	24.16	222.99	21.15	209.77	2
		Farnsworth Lake	17.25	218.10	20.96	185.95	27.05	182.24	32.93	167.03	3
		Average	**12.80**	**253.70**	**17.70**	**220.90**	**24.50**	**197.70**	**26.80**	**185.60**	
Coal Creek near	38,533	Midway Valley	20.89	215.65	29.12	194.04	35.89	176.99	42.29	167.97	1
Cedar City	USGS 10242000	Webster Flat	13.57	232.46	18.70	197.95	24.30	184.64	24.93	181.12	2
		Average	**17.20**	**224.10**	**23.90**	**196.00**	**30.10**	**180.90**	**33.60**	**174.60**	
South Willow near Grantsville	5,426	Rocky Basin-settlemnt	19.09	205.33	23.75	174.14	32.11	171.39	40.01	167.51	1
	USGS 10172800	Mining Fork	16.31	243.66	20.74	177.04	27.81	171.79	32.19	168.74	2
		Average	**17.70**	**224.50**	**22.30**	**175.60**	**30.00**	**171.60**	**36.10**	**168.10**	
Virgin River at Virgin	151,286	Kolob	23.11	229.25	29.08	220.78	36.51	197.43	43.71	196.21	1
	USGS 09406000	Harris Flat	9.71	377.00	15.69	304.18	21.46	300.00	20.11	370.00	2
		Midway Valley	24.76	256.17	34.56	238.40	41.44	209.68	51.05	211.06	3
		Long Flat	9.38	265.88	13.54	286.16	19.20	286.18	18.91	187.00	4
		Average	**16.70**	**282.10**	**23.20**	**262.40**	**29.70**	**248.40**	**33.40**	**241.10**	
Santa Clare above Baker Reservoir	11,620	Gardner Peak	13.00	293.90	16.82	172.15	21.70	167.36	24.45	163.95	1
	USGS 09409100	**Average**	**13.00**	**293.90**	**16.80**	**172.10**	**21.70**	**167.40**	**24.50**	**164.00**	
Utah State Average (%)				**230**		**197**		**183**		**178**	
Standard Deviation				**42**		**38**		**35**		**42**	
Upper 95%				**248**		**213**		**199**		**196**	
Lower 95%				**212**		**180**		**168**		**160**	

Snowpack-related suspension considerations will be assessed on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne River, Price-San Rafael, Dirty Devil, South Eastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. The Weber-Ogden and Provo River – Utah Lake – Jordan River criteria apply to suspension considerations for the Western Uintas project. Since SNOTEL observations are available on a daily basis, suspensions (and cancellation of suspensions) can be made on a daily basis using linear interpolation of the first of month criteria. For the Southern and Central Utah Program, there are 10 listed SNOTEL sites with date-specific snow water equivalent criteria on which suspension decisions can be based.

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

2. Rain-induced Winter Floods

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

3. Severe Weather

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

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

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

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

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

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

APPENDIX B

SEEDING OPERATIONS TABLE, 2019-2020

Table B-1
Generator Hours – Central and Southern Utah, 2019-2020
Storms 1-9

Storm	1	2	3	4	5	6	7	8	9
Dates	**Nov 20-21**	**Nov 25-26**	**Nov 27-30**	**Dec 4-5**	**Dec 8-9**	**Dec 14-15**	**Dec 23-25**	**Jan 1-2**	**Jan 11**
SITES									
10-1		25.25							6
10-2		23							
10-3									
10-4		14							
10-6								13.25	6
10-7								14	6
10-8		1							
10-9		24.5						13.25	5
10-10		25						13.75	
10-11		19.25						14	6
10-12		8.25						13.75	6
11-1					10				
11-2									5.75
11-3								13.25	5.5
11-4		6.25						10.75	
11-5		21.5			9			11.75	5.5
13-1		8.5					15	10.75	5.5
13-3		20.75			11		15	11.75	5.5
13-4									
13-5		12.75			9		15		5.5
13-6		5.75	18						
13-7		3.5	18.5						
13-8		20.5	14		10				5
13-10		21	18.5						5.25
13-11		22.25	18.75		10				
13-12		20.75	18		10			11.75	
14-1		8.5						12.75	5.5

Storm	1	2	3	4	5	6	7	8	9
Dates	**Nov 20-21**	**Nov 25-26**	**Nov 27-30**	**Dec 4-5**	**Dec 8-9**	**Dec 14-15**	**Dec 23-25**	**Jan 1-2**	**Jan 11**
SITES									
14-2		21.25						12.75	5.25
14-3		21							
14-4								12.75	5.25
14-5		21.25	7.25				15	12.75	5.25
14-6		21.25	18.5					12.75	5.25
14-7		21.25	18.5				15	12.5	5.25
17-1					5				
17-2		5.5	18.5						
17-3		5.5	18.25						
17-4		5.5	18.25						
17-5		6.75	19.25				15		
17-6	10		3.25						
17-7	11.5		18.5				17.25		
17-8	11.25								
17-9	11.5		18.5						
17-10	11.25		18.5						
18-2		5.75	17.5		9		15		5
21-1		14.5	8						
21-2			7.5				15.75		
21-5									
21-7			22						
21-8									
21-9									
21-10			19		6		15		
21-11			6						
21-12			5.75						
21-13			35				16		
21-17		21.25	18		6		15		
22-1			9.75				38.5		
22-2	20.25						35.75		
22-3		5.25	19.75				38.5		

Storm	1	2	3	4	5	6	7	8	9
Dates	Nov 20-21	Nov 25-26	Nov 27-30	Dec 4-5	Dec 8-9	Dec 14-15	Dec 23-25	Jan 1-2	Jan 11
SITES									
22-4									
22-5							33		
22-7		5	18		4.75		15		
22-8	20.75	20.75		17		20.5	40		
22-9	20	21	1	12.5	6		39.25		
22-10			2						
22-11		20	19.75						
22-14			5						
22-15	20						38.75		
22-16	20		51.25				37.75		
Storm Total	156.5	555	548.25	29.5	105.75	20.5	500.5	228.25	115.25

Table B-2
Generator Hours – Central and Southern Utah, 2019-2020
Storms 10-18

Storm	10	11	12	13	14	15	16	17	18
Dates	Jan 12-13	Jan 14	Jan 16-17	Jan 26-27	Jan 30	Feb 2-3	Feb 22-23	Mar 1	Mar 8
SITES									
10-1								7.25	
10-2		4							
10-3	12	2							
10-4									
10-6	12					17		7.25	
10-7	12	2				17.5		7.25	
10-8								9.25	
10-9	12	2.5		10		17		7	
10-10				10		17		9.5	
10-11	12			10					
10-12	11			10		17			
11-1			14	10		11			
11-2						11.5			
11-3	12		7						
11-4				10		11.5			
11-5	12		15	10		11			
13-1			14	10		10.75			
13-3	12		14	10		11.25			
13-4									
13-5	12		14	10		11			
13-6				10		11.75			
13-7									
13-8				10		11.25			
13-10			7	10		11.25			
13-11	12		13	10		12			
13-12						11			
14-1	11		8	10					

Storm	10	11	12	13	14	15	16	17	18
Dates	**Jan 12-13**	**Jan 14**	**Jan 16-17**	**Jan 26-27**	**Jan 30**	**Feb 2-3**	**Feb 22-23**	**Mar 1**	**Mar 8**
SITES									
14-2	12		13	10		11.25			
14-3									
14-4			15	6.5		9.75	12		
14-5	12		13	10		11.75	12		
14-6				10	6	11.5			
14-7					6.5	11.5	12		
17-1									
17-2									
17-3						11.5	12		
17-4						11.5	12		
17-5				10		11.5	12		
17-6							12		
17-7							12		
17-8							12		
17-9							12		
17-10							12		
18-2			12	10		11			
21-1				10			12		
21-2					3.75				
21-5									
21-7									
21-8					4.5				
21-9					3.75				
21-10				10	7.25	11.75	12	5.25	
21-11							12		
21-12									
21-13									
21-17									
22-1							12		
22-2							12	2	
22-3							12		

Storm	10	11	12	13	14	15	16	17	18
Dates	**Jan 12-13**	**Jan 14**	**Jan 16-17**	**Jan 26-27**	**Jan 30**	**Feb 2-3**	**Feb 22-23**	**Mar 1**	**Mar 8**
SITES									
22-4							12	6	
22-5				10	7.25	11.5	12	6.25	
22-7						12.75	12		
22-8					7.5		15	17.25	2.5
22-9					9.5		15		
22-10									
22-11									
22-14									
22-15									
22-16									
Storm Total	**166**	**10.5**	**159**	**236.5**	**56**	**358**	**270**	**84.25**	**2.5**

Table B-3
Generator Hours – Central and Southern Utah, 2018-2019
Storms 19-27

Storm	19*	20*	21*	22*	23*	24*	25*	26*	27*	Site Totals
Dates	**Mar 18**	**Mar 19-20**	**Mar 21**	**Mar 23**	**Mar 25-26**	**Mar 29**	**Apr 1-2**	**Apr 8-9**	**Apr 15-16**	
SITES										
10-1										38.5
10-2										27
10-3										14
10-4										14
10-6										55.5
10-7										58.75
10-8										10.25
10-9										91.25
10-10										75.25
10-11										61.25
10-12										66
11-1							12		13	70
11-2										17.25
11-3										37.75
11-4										38.5
11-5							13.5		19.5	128.75
13-1										74.5
13-3		23					13.25		19.25	166.75
13-4		17.5			18.75					36.25
13-5		28			18.5		13.5		19.5	168.75
13-6					7.5		11		19.25	83.25
13-7							10		19.25	51.25
13-8	9.5	29					10		5	124.25
13-10							12		17	102
13-11	8.75				18.5		11		19	155.25
13-12		28			11.5		11			122
14-1										55.75

Storm	19*	20*	21*	22*	23*	24*	25*	26*	27*	Site Totals
Dates	Mar 18	Mar 19-20	Mar 21	Mar 23	Mar 25-26	Mar 29	Apr 1-2	Apr 8-9	Apr 15-16	
SITES										
14-2										85.5
14-3										21
14-4										61.25
14-5										120.25
14-6										85.25
14-7										102.5
17-1	8						12.5			25.5
17-2	9						11			44
17-3					18.5					65.75
17-4					18					65.25
17-5							11			85.5
17-6	5.5	28.5			7.5	8.25	11			86
17-7	8.5					8				75.75
17-8			3.5			6.5				33.25
17-9	7.75					8	11			68.75
17-10	7.75	21				5.5	11.5		16	103.5
18-2	8.25	28.75					13		19	154.25
21-1										44.5
21-2		28.25			14					69.25
21-5	8.25	23.5			6.25			5		43
21-7		9								31
21-8										4.5
21-9										3.75
21-10										86.25
21-11		27.5		3						48.5
21-12										5.75
21-13	9.5	27.5			6.25			15.75		110
21-17										60.25
22-1										60.25
22-2	4	28								102
22-3	9.25	28.5								113.25

Storm	19*	20*	21*	22*	23*	24*	25*	26*	27*	Site Totals
Dates	**Mar 18**	**Mar 19-20**	**Mar 21**	**Mar 23**	**Mar 25-26**	**Mar 29**	**Apr 1-2**	**Apr 8-9**	**Apr 15-16**	
SITES										
22-4	1				6					25
22-5	9.75				6			15.5		111.25
22-7	9.25						12.75			89.5
22-8		15			6					182.25
22-9		29		3	15.5			15		186.75
22-10										2
22-11										39.75
22-14		25.75								30.75
22-15	9	27.25			6.25			15.75		117
22-16	9	5.75	5.25	3.5		7.25		15.5		155.25
Storm Total	**142**	**478.75**	**8.75**	**9.5**	**185**	**43.5**	**211**	**82.5**	**185.75**	

* Seeding funded through lower basin extension

APPENDIX C

PRECIPITATION AND SNOWPACK CONTROL/TARGET STATIONS

PRIMARY TARGET - PRECIPITATION

Site Name	Lat(N)	Long(W)	Elev (Ft)
Control Sites			
Bear Creek Tel, Nv	41°50'	115°27'	8040
Berry Creek Tel, Nv	39°21'	114°39'	9100
Caliente, NV	37°37'	114°31'	4440
Ely, NV	39°17'	114°51'	6250
Flagstaff Airport, AZ	35°08'	111°40'	7000
Jacks Peak Tel, NV	41°32'	116°01'	8420
McGill, Nv	39°24'	114°46'	6340
Pole Creek RS, Tel Nv	41°52'	115°15'	8330
Seligman, Az	35°19'	112°53'	5250
Seventy-Six Ck Tel Nv	41°42'	115°28'	7100
Ward Mountain, Tel #2 Nv	39°08'	114°49'	9200
Wupatki NM, Az	35°31'	111°22'	4908
Target Sites			
Alton	37°26'	112°29'	7040
Beaver Dams	39°08'	111°33'	8000
Big Flat	38°18'	112°21'	10290
Black Fl. UM Ck.	38°41'	111°36'	9400
Box Creek	38°30'	112°02'	9300
Buck Flat	39°08'	111°27'	9800
Castle Valley	37°40'	112°44'	9580
Dills Camp	39°02'	111°28'	9200
Farnsworth Lake	38°46'	111°40'	9600
Gooseberry R.S.	38°48'	111°41'	7920
Hatch	37°39'	112°26'	6910
Kimberly Mine	38°29'	112°23'	9300
Kolob	37°32'	113°03'	9250
Little Grassy Ck.	37°29'	113°51'	6100
Long Flat	37°30'	113°25'	8000
Mammoth-Cottonwood	39°41'	111°19'	8800
Merchant Valley	38°18'	112°26'	8750
Midway Valley	37°34'	112°50'	9800
Pickle Keg Spring	39°02'	111°35'	9600
Pine Creek	38°53'	112°15'	8800

PRIMARY TARGET - PRECIPITATION (continued)

Site Name	Lat(N)	Long(W)	Elev (Ft)
Target Sites			
Red Pine Ridge	39°27'	111°16'	9200
Scofield-Skyland Mine	39°41'	111°12'	8710
Seeley Ck. R.S.	39°19'	111°26'	10000
Webster Flat	37°35'	112°54'	9200
Widtsoe-Esc. # 3	37°50'	111°53'	9500

EASTERN TOOELE TARGET - PRECIPITATION

Site Name	Lat(N)	Long(W)	Elev (Ft)
Control Sites			
Berry Creek, NV	39°21'	114°39'	9100
Diamond Peak, NV	39°34'	115°51'	8040
Farmington Cyn Upr, UT	40°58'	111°48'	8000
Lamoille #3, NV	40°38'	115°24'	7700
Payson R.S., UT	39°56'	111°38'	8050
Ward Mtn #2, NV	39°08'	114°49'	9200
Target Sites			
Rocky Basin Setlmnt, UT	40°26'	112°13'	8900
Tooele, UT	40°32'	112°18'	5072
Vernon Creek, UT	39°56'	112°25'	7500

PRIMARY TARGET - SNOW COURSE AND SNOW PILLOW

Site No.	Lat(N)	Long(W)	Elev (Ft)
Control Sites			
Bright Angel Sc, Az	36°13'	112°04'	8400
Grand Canyon Sc, Az	35°58'	111°58'	7500
Snowbowl #2 Sc, Az	35°19'	111°42'	11,200
Bostetter RS Pil, Id	42°10'	114°11'	7500
Berry Creek, Pil, Nv	39°21'	114°39'	9100
Dorsey Basin Pil, Nv	40°53'	115°12'	8100
Green Mountain Pil, Nv	40°23'	115°32'	8000
Corral Canyon Pil, Nv	40°17'	115°32'	8500
Ward Mountain #2 Pil, Nv	39°08'	114°49'	9200
Pole Creek RS, Pil, Nv	41°52'	115°15'	8330
Target Sites			
Beaver Dams Pil	39°08'	111°33'	8000
Big Flat Pil	38°18'	112°21'	10290
Black Fl UM Creek Pil	38°41'	111°36'	9400
Box Creek Pil	38°30'	112°02'	9300
Buck Flat Pil	39°08'	111°27'	9800
Dill's Camp Pil	39°03'	111°27'	9200
Farnsworth Lake Pil	38°46'	111°40'	9600
Fish Lake Sc	38°33'	111°43'	8700
GBRC Alp Mead. Sc	39°18'	111°27'	10000
GBRC Headqts. Sc	39°19'	111°29'	8700
Gooseberry RS Pil	38°47'	111°41'	8400
Huntington Hrshoe Sc	39°37'	111°19'	9800
Kimberly Mine Pil	38°29'	112°23'	9300
Mammoth-Ctnwood Pil	39°41'	111°19'	8800
Mt. Baldy RS Sc	39°08'	111°30'	9500
Oak Creek SC	39°21'	112°21'	7760
Pickle Keg Spring Pil	39°02'	111°35'	9600
Pine Creek Pil	38°53'	112°15'	8800
Red Pine Ridge Pil	39°28'	111°16'	9200
Seeley Creek R.S. Pil	39°19'	111°26'	10000
Box Springs Pil*	38°30'	112°00'	9300
Thistle Flat Sc	39°14'	111°37'	8500
Upper Joes Valley Sc	39°26'	111°15'	8900

PRIMARY TARGET - SNOW COURSE AND SNOW PILLOW (continued)

Site Name	Lat(N)	Long(W)	Elev (Ft)
Wrigley Creek Sc	39°09'	111°20'	9000
Bryce Canyon Sc	37°38'	112°12'	8000
Castle Valley Pil	37°40'	112°44'	9500
Long Flat Pil	37°30'	113°25'	8000
Midway Valley Pil	37°34'	112°51'	9800
Tall Poles Sc	37°43'	112°51'	8800
Webster Flat Pil	37°59'	112°54'	9200
Widtsoe Esc. #3 Pil	37°50'	111°53'	9500
Yankee Res. Sc	37°32'	112°48'	8700

EASTERN TOOELE TARGET - SNOW COURSE AND SNOW PILLOW

Control Sites			
Baker Creek #2, NV	38°58'	114°17'	8950
Bostetter RS, ID	42°10'	114°11'	7500
Corral Canyon, NV	40°17'	115°32'	8500
Murray Summit, NV	39°14'	114°58'	7250
Payson R.S., UT	39°56'	111°38'	8050
Target Sites			
Bevan's Cabin, UT	40°28'	112°15'	6450
Rocky Basin Settlement, UT	40°26'	112°13'	8900
Vernon Creek, UT	39°56'	112°25'	7500

APPENDIX D

PRECIPITATION AND SNOWPACK ANALYSIS RESULTS TABLES

Note: In the following analyses, the current season data are considered preliminary.

Primary Target Linear Regression
Dec-Mar Precipitation

YEAR	Control	Target	Predicted	Ratio	Increase
Regression (non-seeded) period:					
1957	9.6	12.7	13.1	0.97	-0.4
1958	10.3	13.9	14.3	0.98	-0.3
1959	6.6	8.8	7.9	1.11	0.9
1960	9.3	13.2	12.6	1.05	0.6
1961	6.6	8.5	8.0	1.06	0.5
1962	10.9	14.9	15.2	0.98	-0.3
1963	6.7	9.0	8.2	1.10	0.8
1964	6.9	8.4	8.4	1.00	0.0
1965	9.9	13.3	13.6	0.98	-0.3
1966	7.2	9.3	8.9	1.04	0.4
1967	9.5	12.0	12.8	0.94	-0.8
1968	9.3	12.9	12.6	1.03	0.3
1969	11.9	18.4	17.0	1.09	1.5
1970	8.0	10.6	10.4	1.02	0.2
1971	7.9	9.7	10.1	0.96	-0.4
1972	8.0	7.6	10.3	0.74	-2.7
1973	10.6	14.7	14.7	1.00	0.0
1984	10.6	14.8	14.6	1.01	0.1
Historical Mean	8.9	11.8	11.8	1.00	0.0

Seeded period:

YEAR	Control	Target	Predicted	Ratio	Increase
1974	8.6	11.3	11.3	1.00	0.0
1975	9.1	12.8	12.1	1.06	0.7
1976	7.7	9.9	9.9	1.01	0.1
1977	4.6	6.4	4.6	1.40	1.8
1978	13.0	20.3	18.7	1.08	1.6
1979	10.5	16.3	14.5	1.12	1.8
1980	11.8	20.5	16.7	1.23	3.9
1981	6.6	9.3	8.0	1.16	1.3
1982	11.4	16.9	16.1	1.05	0.8
1983	10.8	17.5	15.0	1.17	2.5
1985*	7.0	11.3	8.6	1.31	2.7
1986*	9.1	10.9	12.2	0.89	-1.3
1987*	6.6	9.7	8.0	1.21	1.7
1988	6.2	9.8	7.2	1.36	2.6
1989	8.0	10.2	10.3	0.99	-0.1

YEAR	Control	Target	Predicted	Ratio	Increase
1990	6.5	9.1	7.8	1.17	1.3
1991	6.6	10.8	8.0	1.34	2.7
1992	6.4	10.2	7.6	1.34	2.6
1993	13.1	19.7	19.0	1.04	0.7
1994	5.7	8.7	6.5	1.35	2.3
1995	9.0	14.0	12.0	1.17	2.0
1996	9.1	12.9	12.2	1.05	0.7
1997	8.8	12.2	11.6	1.05	0.5
1998	9.4	14.4	12.6	1.14	1.8
1999	5.7	6.9	6.4	1.07	0.4
2000	8.3	12.4	10.8	1.15	1.7
2001	5.9	9.5	6.8	1.39	2.7
2002	5.9	6.2	6.7	0.92	-0.6
2003	5.8	9.6	6.6	1.45	3.0
2004	7.3	11.0	9.2	1.20	1.8
2005	10.3	15.9	14.2	1.13	1.8
2006	9.7	13.7	13.1	1.04	0.5
2007	6.3	7.2	7.4	0.98	-0.2
2008	8.8	15.1	11.7	1.28	3.3
2009	8.7	13.1	11.6	1.13	1.5
2010	8.4	13.8	11.1	1.24	2.7
2011	10.3	16.6	14.3	1.16	2.3
2012	6.6	8.7	7.9	1.09	0.7
2013	7.1	9.2	8.9	1.04	0.4
2014	6.1	7.9	7.1	1.10	0.7
2015	6.5	8.4	7.7	1.09	0.7
2016	8.8	11.4	11.7	0.98	-0.3
2017	12.6	16.1	18.0	0.89	-2.0
2018	6.1	8.5	7.2	1.18	1.3
2019	11.0	15.7	15.3	1.03	0.4
2020	8.0	10.1	10.4	0.98	-0.2
Seeded Mean	8.3	12.1	10.8	**1.12**	**1.3**

*Seeding conducted in adjacent areas, but not target area

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.955721
R Square	0.913403

	Coefficients
Intercept	-3.173422
X Variable 1	1.688715

Eastern Tooele Target Linear Regression
Dec-Mar Precipitation

YEAR	Control	Target	Predicted	Ratio	Increase
Regression (non-seeded) period					
1957	13.3	10.6	10.9	0.97	-0.4
1958	16.7	11.7	13.9	0.84	-2.2
1959	10.5	8.4	8.4	0.99	-0.1
1960	13.8	11.2	11.4	0.98	-0.2
1961	9.2	6.7	7.3	0.92	-0.6
1962	15.8	11.6	13.2	0.88	-1.6
1963	10.6	7.7	8.6	0.89	-0.9
1964	11.4	7.8	9.3	0.84	-1.5
1965	16.4	12.0	13.6	0.88	-1.6
1966	10.5	7.4	8.5	0.87	-1.1
1967	16.1	10.1	13.4	0.75	-3.3
1968	15.2	10.7	12.6	0.85	-1.9
1969	20.6	17.7	17.3	1.02	0.4
1970	11.7	7.2	9.5	0.76	-2.3
1971	13.3	15.4	11.0	1.40	4.4
1972	11.2	7.6	9.1	0.84	-1.5
1973	18.2	20.1	15.2	1.32	4.9
1974	14.5	8.7	12.0	0.73	-3.3
1975	16.0	12.8	13.3	0.96	-0.5
1983	18.1	16.1	15.1	1.06	1.0
1984	18.7	13.7	15.6	0.88	-1.9
1985	11.0	11.6	8.9	1.29	2.6
1986	16.1	13.8	13.4	1.03	0.4
1987	10.6	11.2	8.6	1.30	2.6
1988	9.5	9.5	7.6	1.25	1.9
1993	16.9	17.3	14.1	1.23	3.3
1994	11.4	10.4	9.3	1.13	1.2
1995	15.3	14.8	12.6	1.17	2.2
Historical Mean	14.0	11.6	11.6	1.00	0.0

Seeded period:

YEAR	Control	Target	Predicted	Ratio	Increase
1976	11.5	10.3	9.4	1.10	0.9
1977	8.6	6.6	6.9	0.96	-0.2
1978	19.4	20.7	16.3	1.27	4.4
1979	13.9	12.5	11.5	1.09	1.0
1980	18.8	19.6	15.8	1.24	3.8
1981	11.5	8.9	9.3	0.95	-0.5
1982	19.4	15.5	16.3	0.95	-0.8
1989	13.2	11.0	10.8	1.02	0.2
1990	9.6	9.8	7.7	1.27	2.1

YEAR	Control	Target	Predicted	Ratio	Increase
1991	9.3	8.4	7.4	1.13	1.0
1992	9.2	7.4	7.4	1.01	0.1
1996	17.1	14.2	14.2	1.00	0.0
1997	15.5	15.0	12.9	1.16	2.1
1998	17.5	20.2	14.6	1.39	5.6
1999	10.9	9.3	8.8	1.05	0.5
2000	15.1	15.2	12.5	1.21	2.6
2001	10.3	9.4	8.3	1.12	1.0
2002	10.4	8.4	8.4	1.00	0.0
2003	9.5	8.7	7.6	1.14	1.1
2004	13.5	15.0	11.1	1.34	3.8
2005	16.1	15.4	13.4	1.15	2.0
2006	17.6	15.4	14.7	1.05	0.7
2007	10.3	9.9	8.3	1.19	1.6
2008	15.4	14.7	12.7	1.15	2.0
2009	15.9	13.6	13.2	1.03	0.4
2010	13.6	11.5	11.2	1.03	0.3
2011	17.9	16.6	14.9	1.11	1.6
2012	8.9	8.5	7.1	1.19	1.3
2013	10.3	9.5	8.3	1.15	1.2
2014	11.1	10.4	9.0	1.15	1.3
2015	7.7	6.2	6.0	1.03	0.2
2016	14.4	13.2	11.9	1.10	1.2
2017	20.0	18.8	16.8	1.12	2.0
2018	9.7	8.6	7.8	1.10	0.8
2019	18.9	17.3	15.5	1.11	1.5
2020	10.6	8.4	8.6	0.98	-0.2
Seeded Mean	13.4	12.3	11.0	**1.12**	**1.3**

SUMMARY OUTPUT

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

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

Primary Target
Apr 1 Snow Water Content

YEAR	Control	Target	Predicted	Ratio	Increase
Regression (non-seeded) period:					
1956	14.9	12.3	15.1	0.82	-2.7
1957	15.3	16.9	15.4	1.10	1.5
1958	20.2	20.6	20.5	1.00	0.1
1959	9.6	10.4	9.6	1.09	0.8
1960	12.4	13.9	12.5	1.11	1.4
1961	12.7	11.3	12.7	0.89	-1.4
1962	20.3	20.1	20.6	0.98	-0.5
1963	8.9	10.3	8.8	1.17	1.5
1964	12.0	11.4	12.1	0.95	-0.7
1965	16.2	17.9	16.4	1.09	1.5
1966	11.2	10.5	11.2	0.93	-0.7
1967	11.5	10.8	11.5	0.94	-0.7
1968	13.5	16.8	13.6	1.24	3.3
1969	21.0	23.1	21.4	1.08	1.7
1970	14.3	15.2	14.4	1.06	0.8
1971	14.9	14.4	15.1	0.96	-0.6
1972	12.2	8.4	12.3	0.69	-3.9
1973	21.6	20.7	21.9	0.94	-1.2
1984	23.8	24.1	24.2	0.99	-0.2
Historical Mean	15.1	15.2	15.2	1.00	0.0

YEAR	Control	Target	Predicted	Ratio	Increase
1974	13.9	15.6	14.0	1.11	1.6
1975	18.0	17.3	18.3	0.95	-1.0
1976	12.7	12.9	12.8	1.01	0.2
1977	8.1	8.2	8.0	1.02	0.2
1978	18.6	21.8	18.9	1.15	2.9
1979	18.0	21.4	18.2	1.17	3.2
1980	19.3	23.6	19.6	1.20	4.0
1981	9.6	10.2	9.6	1.06	0.6
1982	20.3	20.5	20.7	0.99	-0.2
1983	23.1	26.0	23.6	1.10	2.4
1985*	16.3	16.5	16.5	1.00	0.0
1986*	13.8	15.7	13.9	1.13	1.8
1987*	11.2	13.0	11.2	1.17	1.9
1988	10.5	13.1	10.5	1.25	2.7
1989	14.5	11.3	14.6	0.77	-3.4
1990	9.2	10.5	9.1	1.16	1.4
1991	12.3	12.8	12.3	1.04	0.5
1992	11.7	12.1	11.7	1.04	0.4

YEAR	Control	Target	Predicted	Ratio	Increase
1993	20.1	21.3	20.4	1.04	0.9
1994	9.3	10.8	9.3	1.17	1.6
1995	17.8	16.6	18.0	0.92	-1.4
1996	13.7	14.6	13.8	1.06	0.8
1997	15.5	15.1	15.7	0.96	-0.6
1998	17.1	16.7	17.4	0.96	-0.7
1999	10.3	8.1	10.3	0.79	-2.2
2000	12.8	13.7	12.9	1.06	0.8
2001	10.8	11.3	10.8	1.04	0.5
2002	10.4	9.6	10.4	0.92	-0.8
2003	9.5	12.1	9.5	1.28	2.6
2004	9.3	10.2	9.2	1.11	1.0
2005	20.8	20.1	21.1	0.95	-1.0
2006	16.7	17.4	16.9	1.03	0.5
2007**	7.9	6.8	7.8	0.87	-1.0
2008	15.1	16.1	15.2	1.06	0.8
2009	12.9	12.7	13.0	0.98	-0.2
2010	14.7	15.1	14.8	1.02	0.3
2011	16.0	20.1	16.2	1.24	3.9
2012**	7.3	7.9	7.1	1.11	0.8
2013	8.9	9.3	8.8	1.06	0.5
2014	9.5	9.9	9.4	1.05	0.5
2015**	5.0	6.1	4.7	1.28	1.3
2016	14.2	12.8	14.4	0.89	-1.5
2017**	16.4	13.9	16.6	0.84	-2.7
2018	8.2	7.9	8.1	0.97	-0.2
2019	18.7	19.5	18.9	1.03	0.6
2020	11.5	14.0	11.6	1.21	2.4
Seeded Mean	13.9	14.7	14.0	**1.04**	**0.6**

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

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.935556 3
R Square	0.875265 7
Adjusted R Square	0.867928 4
Standard Error	1.740763 6
Observations	19

YEAR	Control	Target	Predicted	Ratio	Increase

	Coefficients
	- 0.3789664
Intercept	0
	1.0355608
X Variable	5

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

YEAR	North Ctrl	South Ctrl	Target	Predicted	Ratio	Increase
Regression period:						
1956	20.5	9.3	12.3	14.5	0.85	-2.2
1957	16.8	13.7	16.9	15.9	1.06	1.0
1958	25.5	14.9	20.6	20.3	1.02	0.3
1959	12.3	6.9	10.4	9.5	1.10	0.9
1960	13.7	11.2	13.9	12.9	1.08	1.0
1961	17.6	7.7	11.3	12.3	0.93	-0.9
1962	22.8	17.7	20.1	21.1	0.96	-0.9
1963	10.2	7.6	10.3	9.1	1.14	1.2
1964	17.1	6.9	11.4	11.5	0.99	-0.1
1965	20.0	12.4	17.9	16.4	1.09	1.5
1966	11.1	11.3	10.5	11.9	0.88	-1.4
1967	14.4	8.5	10.8	11.4	0.94	-0.7
1968	12.6	14.3	16.8	14.6	1.16	2.3
1969	21.1	21.0	23.1	22.5	1.03	0.6
1970	18.1	10.4	15.2	14.3	1.07	1.0
1971	21.0	8.9	14.4	14.4	1.00	0.0
1972	19.1	5.4	8.4	11.3	0.75	-2.9
1973	20.9	22.3	20.7	23.3	0.89	-2.6
1984	36.7	10.9	24.1	22.3	1.08	1.8
Historical Mean	18.5	11.6	15.2	15.2	1.00	0.0

YEAR	North Ctrl	South Ctrl	Target	Predicted	Ratio	Increase
Seeded Period:						
1974	20.9	7.0	15.6	13.1	1.19	2.5
1975	24.4	11.6	17.3	17.7	0.98	-0.4

1976	18.2	7.1	12.9	12.1	1.07	0.8
1977	9.9	6.3	8.2	8.1	1.01	0.1
1978	19.5	17.7	21.8	19.7	1.11	2.1
1979	19.0	17.0	21.4	19.0	1.13	2.4
1980	19.6	19.0	23.6	20.6	1.15	3.0
1981	10.1	9.1	10.2	10.1	1.01	0.1
1982	25.8	14.9	20.5	20.4	1.00	0.0
1983	24.6	21.6	26.0	24.4	1.06	1.6
1985*	17.8	14.9	16.5	17.1	0.97	-0.5
1986*	16.2	11.3	15.7	14.0	1.12	1.6
1987*	12.2	10.2	13.0	11.6	1.12	1.4
						2.8
1988	13.5	7.4	13.1	10.3	1.27	
YEAR	North Ctrl	South Ctrl	Target	Predicted	Ratio	Increase
1990	11.3	7.0	10.5	9.2	1.15	1.4
1991	12.7	11.9	12.8	13.0	0.99	-0.1
1992	10.0	13.3	12.1	12.8	0.95	-0.7
1993	17.2	22.9	21.3	22.2	0.96	-0.9
1994	9.9	8.7	10.8	9.7	1.12	1.1
1995	15.7	19.8	16.6	19.5	0.85	-2.9
1996	20.4	7.0	14.6	12.9	1.13	1.7
1997	19.7	11.3	15.1	15.5	0.97	-0.4
1998	18.3	15.9	16.7	18.0	0.93	-1.3
1999	14.8	5.7	8.1	9.7	0.83	-1.6
2000	16.0	9.6	13.7	12.8	1.07	0.9
2001	11.3	10.3	11.3	11.3	1.00	0.0
2002	15.8	5.0	9.6	9.7	0.99	-0.1
2003	10.1	8.9	12.1	9.9	1.22	2.2
2004	12.7	5.9	10.2	8.9	1.15	1.3
2005	18.4	23.1	20.1	22.8	0.88	-2.7
2006	23.9	9.4	17.4	16.0	1.09	1.4
2007**	11.2	4.5	6.8	7.4	0.91	-0.6
2008	17.7	12.5	16.1	15.4	1.04	0.6
2009	15.3	10.5	12.7	13.1	0.97	-0.4
2010	14.0	15.3	15.1	15.8	0.95	-0.7
2011	19.6	12.4	20.1	16.2	1.24	3.9
2012**	9.5	5.1	7.9	7.1	1.12	0.9
2013	12.0	5.8	9.3	8.6	1.08	0.7
2014	14.1	4.8	9.9	8.8	1.12	1.0
2015**	6.0	3.9	6.1	4.9	1.26	1.2
2016	21.0	7.4	12.8	13.5	0.95	-0.6
2017**	18.8	13.9	13.9	16.9	0.82	**-3.0**
2018	12.1	4.3	7.9	7.7	1.03	0.3
2019	21.9	15.4	19.5	19.2	1.02	0.4
2020	14.3	8.7	14.0	11.5	1.21	2.4
Seeded Mean	16.6	11.3	14.7	14.2	**1.03**	**0.5**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.949996055
R Square	0.902492504

	Coefficients
	-
Intercept	0.260923565
X North	0.417766179
X South	0.666458753

Eastern Tooele Target
Apr 1 Snow Water Content

YEAR	Control	Target	Predicted	Ratio	Increase
Regression (non-seeded) period:					
1956	16.3	8.9	16.7	0.54	-7.7
1957	14.2	16.0	14.4	1.11	1.6
1958	20.9	16.2	21.6	0.75	-5.4
1959	10.6	10.2	10.5	0.97	-0.3
1960	12.0	16.2	12.0	1.35	4.2
1961	12.8	10.5	12.9	0.82	-2.3
1962	20.7	18.8	21.3	0.88	-2.5
1963	7.9	7.1	7.6	0.93	-0.5
1964	13.8	14.0	14.0	1.00	0.0
1965	17.0	16.3	17.4	0.93	-1.1
1966	11.1	9.4	11.1	0.85	-1.6
1967	12.7	11.9	12.7	0.93	-0.9
1968	12.5	14.0	12.6	1.12	1.4
1969	22.4	25.5	23.2	1.10	2.3
1970	14.7	11.9	14.9	0.79	-3.1
1971	16.6	16.6	17.0	0.98	-0.4
1972	15.3	8.7	15.5	0.56	-6.9
1973	20.4	32.1	21.0	1.53	11.1
1974	17.2	13.1	17.6	0.74	-4.5
1975	18.1	20.1	18.6	1.08	1.5
1983	22.4	21.0	23.2	0.90	-2.2
1984	27.1	30.8	28.1	1.10	2.7
1985	15.0	20.3	15.2	1.33	5.1
1986	16.0	12.8	16.3	0.79	-3.5
1987	11.3	15.3	11.3	1.36	4.0
1988	11.7	12.2	11.7	1.05	0.6
1993	16.1	19.9	16.4	1.21	3.5
1994	10.0	11.5	9.9	1.16	1.6
1995	13.8	17.0	13.9	1.22	3.1

YEAR	Control	Target	Predicted	Ratio	Increase
Historical Mean	15.5	15.8	15.8	1.00	0.0

Seeded period:

YEAR	Control	Target	Predicted	Ratio	Increase
1976	15.7	15.6	16.0	0.98	-0.4
1977	6.2	9.3	5.8	1.59	3.5
1978	17.4	21.1	17.8	1.18	3.3
1979	18.9	18.0	19.4	0.93	-1.4
1980	19.0	24.4	19.5	1.25	4.8
1981	9.3	12.5	9.2	1.36	3.3
1982	21.4	19.6	22.1	0.89	-2.5
1989	13.9	9.9	14.1	0.70	-4.2
1990	10.7	12.4	10.7	1.16	1.7
1991	10.2	10.5	10.1	1.05	0.5
1992	8.7	10.3	8.5	1.21	1.8
1996	14.5	12.8	14.7	0.87	-1.9
1997	14.8	17.9	15.0	1.19	2.9
1998	14.8	23.4	15.0	1.56	8.4
1999	10.1	8.8	10.0	0.88	-1.2
2000	11.2	15.9	11.2	1.42	4.7
2001	8.7	11.4	8.5	1.35	3.0
2002	11.2	11.0	11.2	0.98	-0.2
2003	8.5	9.6	8.3	1.16	1.3
2004	10.2	15.0	10.1	1.49	4.9
2005	18.0	20.2	18.5	1.09	1.7
2006	16.6	16.3	17.0	0.96	-0.6
2007*	6.8	7.2	6.4	1.11	0.7
2008	14.3	17.5	14.4	1.21	3.1
2009	12.6	13.9	12.6	1.10	1.2
2010	12.2	13.0	12.2	1.06	0.8
2011	16.0	21.9	16.3	1.34	5.5
2012*	8.2	7.2	7.9	0.91	-0.7
2013	7.9	10.0	7.7	1.30	2.3
2014	10.1	8.3	9.9	0.83	-1.7
2015*	4.1	1.5	3.6	0.43	-2.0
2016	13.6	12.0	13.8	0.87	-1.8
2017*	12.9	13.8	13.0	1.06	0.8
2018	8.3	5.3	8.1	0.66	-2.8
2019	19.5	21.4	20.0	1.07	1.4
2020	10.7	11.5	10.7	1.08	0.8
Seeded Mean	13.0	14.4	13.1	**1.10**	**1.3**

* Not included in mean due to early-season snowmelt

SUMMARY OUTPUT

YEAR	Control	Target	Predicted	Ratio	Increase

Regression Statistics	
Multiple R	0.766963
R Square	0.588233
Adjusted R Square	0.572982
Standard Error	3.975414
Observations	29

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-0.80605	2.774503	-0.29052	0.773637	-6.49886
X Variable 1	1.068717	0.172081	6.210555	1.22E-06	0.715637

APPENDIX E

GLOSSARY OF RELEVANT METEOROLOGICAL TERMS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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