THE CONDUCT AND EVALUATION OF A CLOUD SEEDING PROGRAM FOR SIX CREEKS PROGRAM DURING THE 2018-2019 WINTER SEASON

Prepared for

Salt Lake City Department of Public Utilities

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1.0 INTRODUCTION

Salt Lake City sponsored earlier winter cloud seeding programs targeting the Six Creek's drainage basins in water years 1989 through 1996. North American Weather Consultants (NAWC) operated these programs. NAWC analysis of potential effects of the seeding indicated positive effects (~6% to 17% for water years 1989 and 1990, Thompson, et al, 1990). It was NAWC understanding that this program was discontinued following water year 1996 due to budgetary considerations.

The Salt Lake City Department of Public Utilities (SLCDPU) was contacted by the Utah Division of Water Resources regarding the cloud-seeding program. Following discussions, SLCDPU expressed an interest in re-establishing a cloud seeding program to impact the Six Creek's drainage basins that provide runoff to the Salt Lake Valley. This interest was expressed in a letter to Candice Hasenyager, coordinator of the Utah Division of Water Resources cloud seeding programs, that would enable cost sharing of this program with the Utah Division of Water Resources (e.g., up to 50% cost sharing state support).

NAWC contacted the SLCDPU and it was agreed that NAWC would prepare a proposal to conduct a program for the 2018-2019 winter season (NAWC proposal (# 18-429). The goal of the program would be to augment the flows of City Creek, Emigration Creek, Parleys Creek, Mill Creek, Big Cottonwood Creek and Little Cottonwood Creek. Figure 1.1 provides a map of the proposed target area (e.g., six creeks drainage areas above 6000 feet MSL). The SLCDPU accepted this proposal and an agreement was signed effective November 19, 2018.

The program was operational from mid-December 2018 through April 18, 2019. The program was scheduled to run through April 30th, but seeding operations were terminated early due to high snow water contents in the target basins. The 2018-2019 winter season brought significant amounts of snow to all mountainous areas of Utah with a statewide average snow water content on April 1, 2019 of 140%. The remainder of this report will discuss the design, operation and evaluation of this program.

Once the cloud seeding program was established, some public interest was generated in the form of special television coverage on KSL, channel 5 and Fox channel 13 and a news feature in the Deseret News. For further information regarding media releases, please refer to Appendix A.

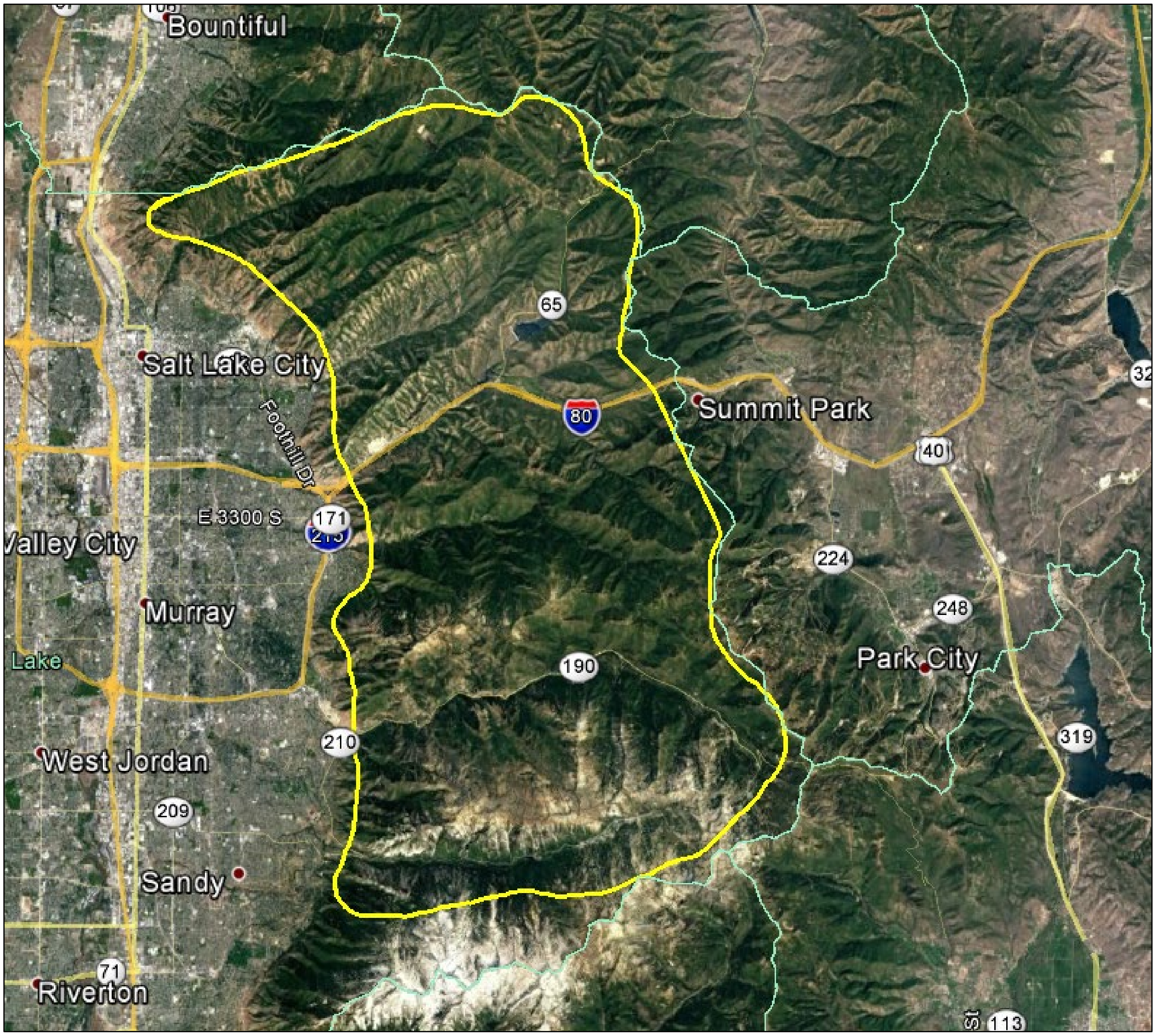

Figure 1.1 Six Creeks Target Area

2.0 CLOUD SEEDING THEORY

This section provides a brief overview of the theory of cloud seeding.

Clouds form when temperatures in the atmosphere reach saturation, that is, a relative humidity of 100%. This saturated condition causes water vapor to condense around a nucleus forming a cloud droplet. These nuclei, which may be small particles like salts formed through evaporation off the oceans, are known as "cloud condensation nuclei." Clouds can be composed of water droplets, ice crystals or a combination of the two. Clouds that are entirely warmer than freezing are sometimes referred to as "warm clouds". Likewise, clouds that are colder than freezing are sometimes referred to as "cold clouds." Cold clouds may have cloud bases that are warmer than freezing. Precipitation can occur naturally from both types of clouds.

In warm clouds, cloud droplets that survive long enough (and especially when cloud drops are of different sizes) may collide and grow to raindrop sizes, subsequently falling to the ground as rain. This process is known as "collision/coalescence." This process is especially important in tropical clouds but can also occur in more temperate climates.

In cold regions (< 0°C) of clouds, cloud water droplets may not freeze. The reason for this is the purity of the cloud water droplets. In a laboratory environment, pure water droplets can remain unfrozen down to a temperature of -39°C. Natural impurities in the atmosphere can cause cloud droplets that are colder than freezing (usually referred to as supercooled) to freeze. These supercooled cloud droplets are what causes icing to occur on aircraft. The natural impurities often consist of tiny soil particles or bacteria. These impurities are referred as "freezing nuclei." A supercooled cloud droplet can be frozen when it collides with one of these natural freezing nuclei thus forming an ice crystal. This process is known as "contact nucleation." A water droplet may also be formed on a freezing nucleus, which has hygroscopic (water attracting) characteristics. This same nucleus can then cause the water droplet to freeze at temperatures less than about -5˚C forming an ice crystal. This process is known as "condensation/freezing." Once an ice crystal is formed within a cloud it will grow as cloud droplets around it evaporate and add their mass to the ice crystal, eventually forming a snowflake (diffusional growth). Ice crystals can also gain mass as they fall and contact, then freeze, other supercooled cloud droplets, a process known as "riming." These snowflakes may reach the ground as snow if temperatures at the surface are 0˚C or colder. They may reach the surface as raindrops if surface temperatures are warmer than freezing.

Research conducted in the late 1940's demonstrated that tiny particles of silver iodide could mimic Mother Nature and serve as freezing nuclei at temperatures colder than about -5°C. In fact, these silver iodide particles were shown to be much more active at temperatures of between -5°C to -15°C than the natural freezing nuclei found in the atmosphere. Therefore, most modern day attempts to modify clouds to produce more precipitation (or reduce hail) have used silver iodide as a seeding agent. By definition, these programs are conducted to affect colder portions of clouds; typically cloud regions that are -5°C or colder (e.g., "cold clouds"). These programs are sometimes called cold cloud or glaciogenic seeding programs. Glaciogenic cloud seeding can be conducted in summer convective clouds whose tops pass through the -5°C level, and in winter stratiform clouds that reach at least the -5°C level.

There has been some research and operational programs designed to increase precipitation from "warm clouds." The seeding agents used in these programs are hygroscopic (water attracting) particles, typically some kind of salt (e.g., calcium chloride). These salt particles can form additional cloud droplets, which may add to the rainfall reaching the ground. This seeding technique, which is sometimes referred to as warm cloud or hygroscopic seeding, can also modify the warm portion of clouds that then grow vertically to reach temperatures colder than freezing. A research program conducted in South Africa targeting these types of clouds indicated that such seeding did increase the amount of rainfall from the seeded clouds.

In summary, most present day winter cloud seeding programs introduce a seeding agent, such as microscopic sized silver iodide particles, into clouds whose temperatures are colder than freezing. These silver iodide particles can cause cloud droplets to freeze, forming ice crystals. These ice crystals can grow to snowflake sizes, falling to the ground as snow or as rain depending on the surface temperature.

3.0 PROJECT DESIGN

3.1 Background

Operational procedures during the 2018-2019 Six Creeks 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 some 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.

3.2 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 seeding is 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 3-1 provides the seeding criteria, which NAWC has established for other 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 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 3-1, item 4) and were therefore not seeded. The existence of low-level inversions 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 3-1

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).

3.3 Equipment and Project Set-Up

The nine seeding generator site locations are shown in Figure 3.1, with site information in Table 3-2. It should be noted that winds during winter storms in Utah typically blow from the west toward the east, usually from the southwest before frontal passages and from the northwest following frontal passages. The sites were located to maximize their potential use during typical storm periods.

Figure 3.1 Target Area and Seeding Site Locations

Table 3-2
Seeding Site Locations

Site Number	Name	Latitude	Longitude	Elevation (feet)
1	Baskin Reservoir	40.7438	-111.8183	4835
2	Mountain Dell Treatment	40.7488	-111.7227	5380
3	45th South Pump Station	40.6747	-111.8014	4950
4	White Reservoir	40.6772	-111.7760	5620
5	Big Cottonwood Canyon Water Treatment	40.6189	-111.7818	4993
6	Little Cottonwood	40.576	111.798	5170
7	Wasatch Resort	40.571	111.763	5650
8	Metro Water Treatment Plant	40.589	111.800	4990
9	Alpine	40.479	111.755	5440

The cloud seeding equipment at each site includes a cloud seeding generator unit and a propane gas supply tank. Figure 3.2 shows an example of one of the generator sites, in this case, the White Reservoir site. 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 formula is designed 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 seeding units were 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. Three of the sites for the Six Creeks program were sited on Salt Lake City property and were operated by Salt Lake City personnel. The project meteorologist would contact a dispatcher and this dispatcher would relay to personnel, which sites needed to be activated or deactivated. The remainder of the sites were operated by NAWC personnel or local residents trained as operators and contracted by NAWC to operate the units when requested to do so by a NAWC meteorologist.

Figure 3.2 White Reservoir Cloud Seeding Site

When a site was in operation, the propane gas pressurized the solution tank, which forces the solution 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 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 "seeding window" (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 Pacific Ocean 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 which the winds are blowing. For example, a southwest wind means the winds are blowing towards the northeast.

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. Appendix A provides the resulting suspension criteria. Seeding scheduled that were scheduled to run through April 30th were terminated April 18th due to high snow water contents in the target area basins. There were no other seeding suspensions during the 2018-2019 winter season.

4.0 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 weather cameras. 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 4.1 – 4.3 show examples of some of the available weather information that was used in this decision-making process during the 2018-2019 winter season. Figure 4.4 provides predictions of ground-based seeding plume dispersion for a discrete storm period that impacted the Six Creek's target area in early February using the National Oceanic and Atmospheric Administration's HYSPLIT model (Appendix B provides more information on this model). This model helps to estimate the horizontal and vertical spread of a plume from potential ground-based seeding sites in real-time, based on wind fields contained in the weather forecast models.

Global and regional forecast models are a cornerstone of modern weather forecasting, and an important tool for operational meteorologists. These models forecast a variety of parameters at different levels of the atmosphere, including winds, temperatures, moisture, and surface parameters such as accumulated precipitation. An example of a display from the global GFS forecast model is shown in Figure 4.5, where the left panel displays humidity, winds and temperatures at the 700 mb level (approximately 10,000 feet). The right panel indicates precipitation accumulation as well as surface winds and pressure.

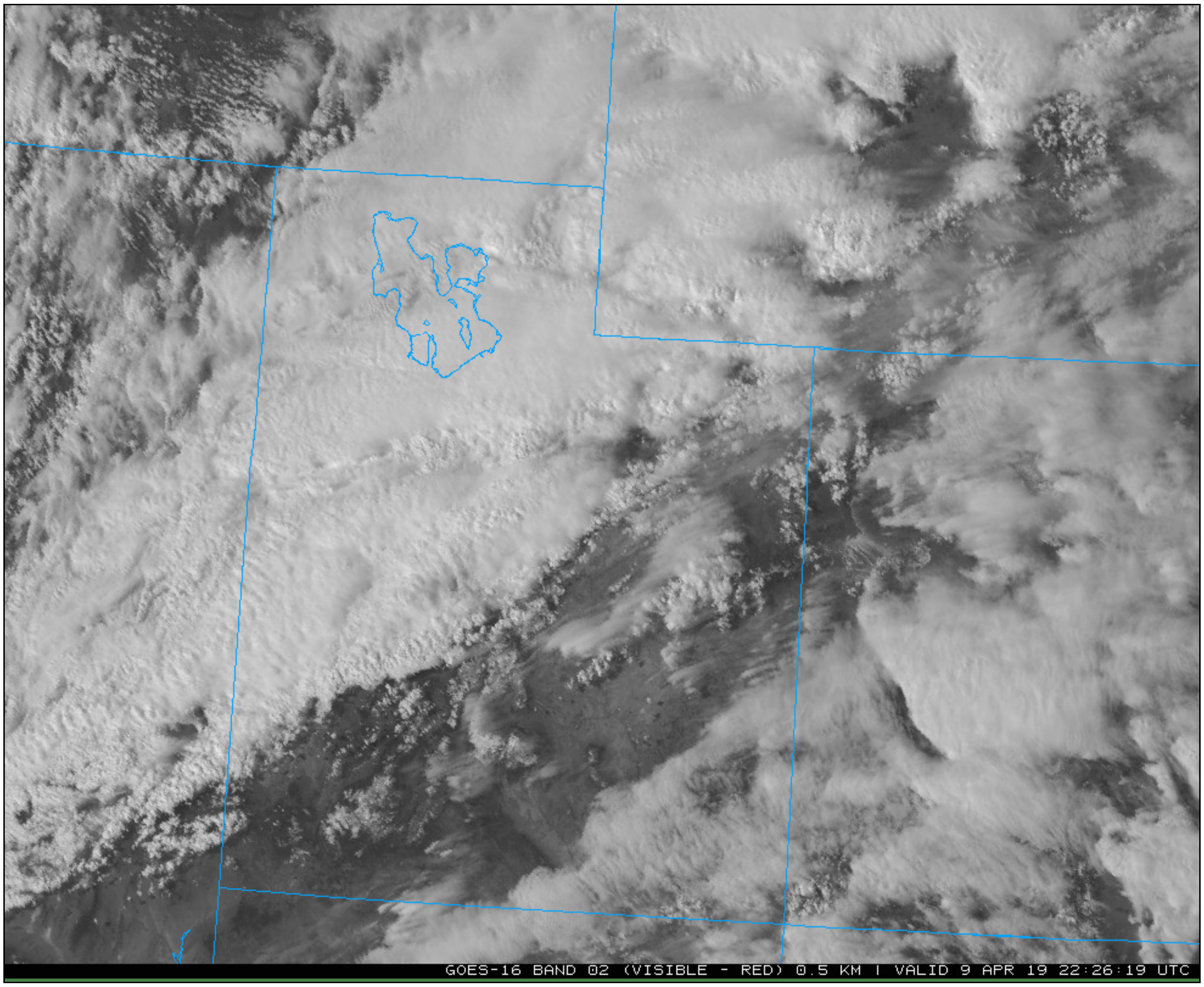

Figure 4.1 Visible Satellite Image at 1626 MDT on April 9, 2019

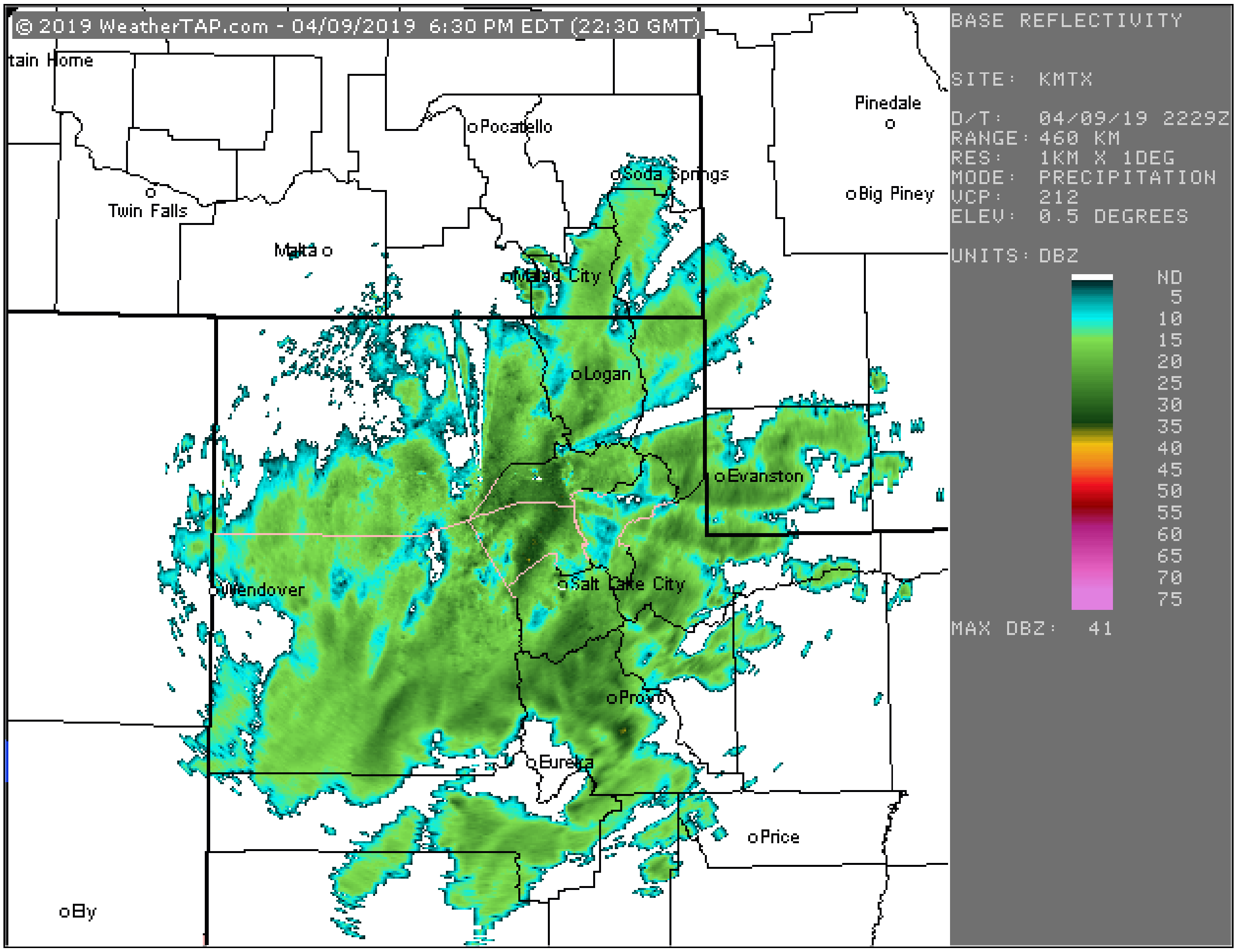

Figure 4.2 Base Reflectivity Image, Salt Lake City area, at 1630 MDT April 9

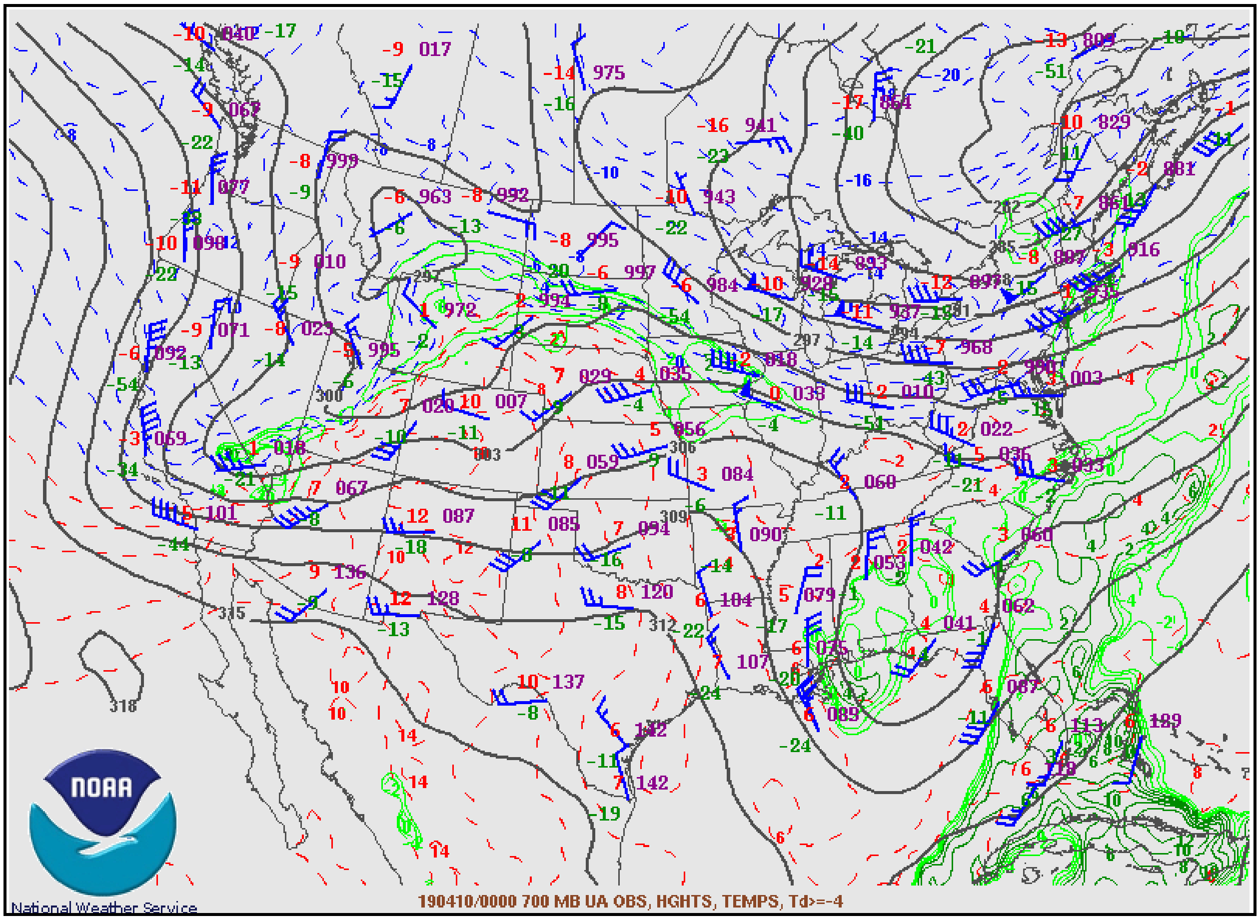

Figure 4.3   700 mb Map at 1600 MDT on April 9, 2019

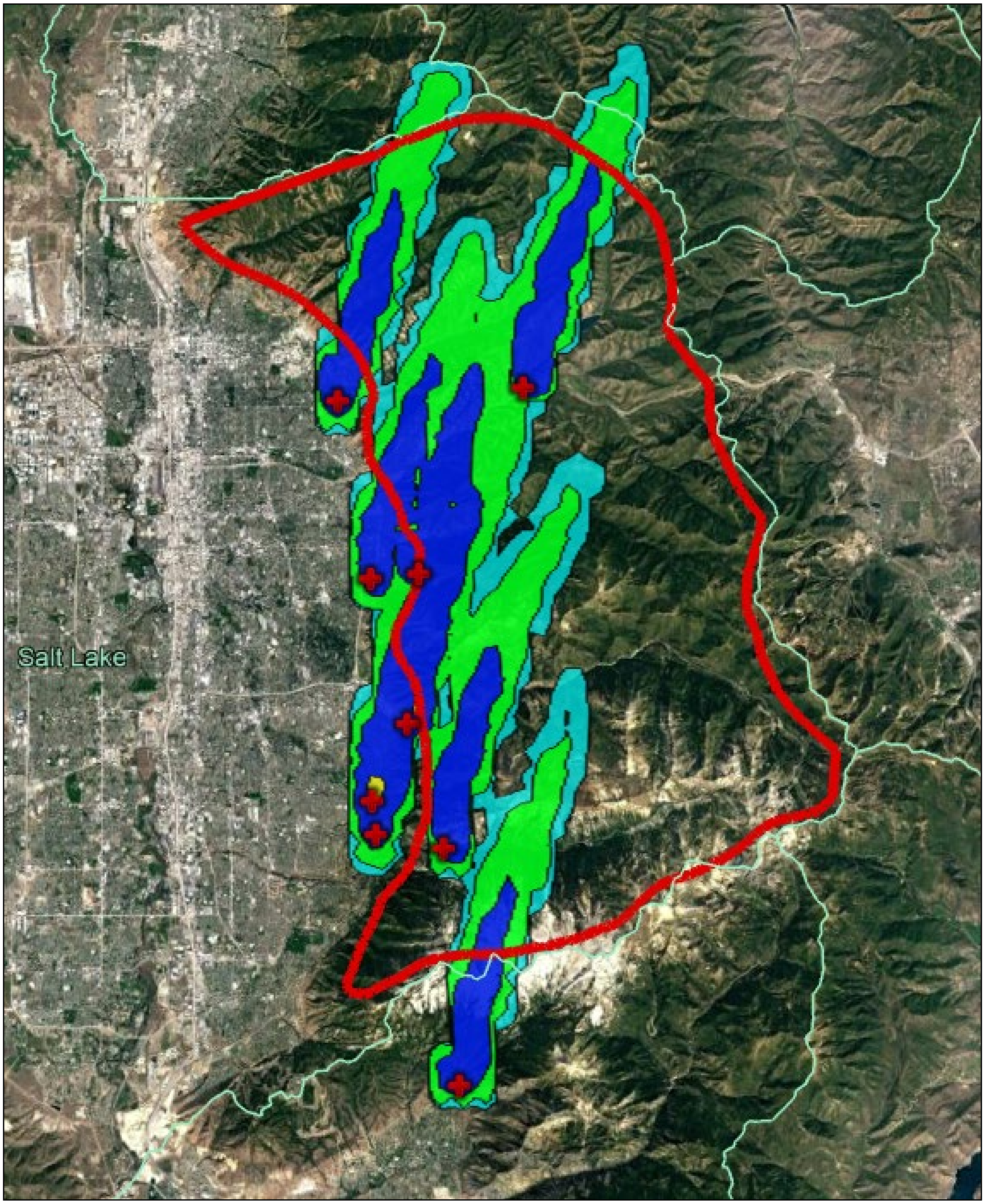

Figure 4.4 HYSPLIT plume dispersion forecast during a seeded storm period on February 5, 2019. Red outline is the target area.

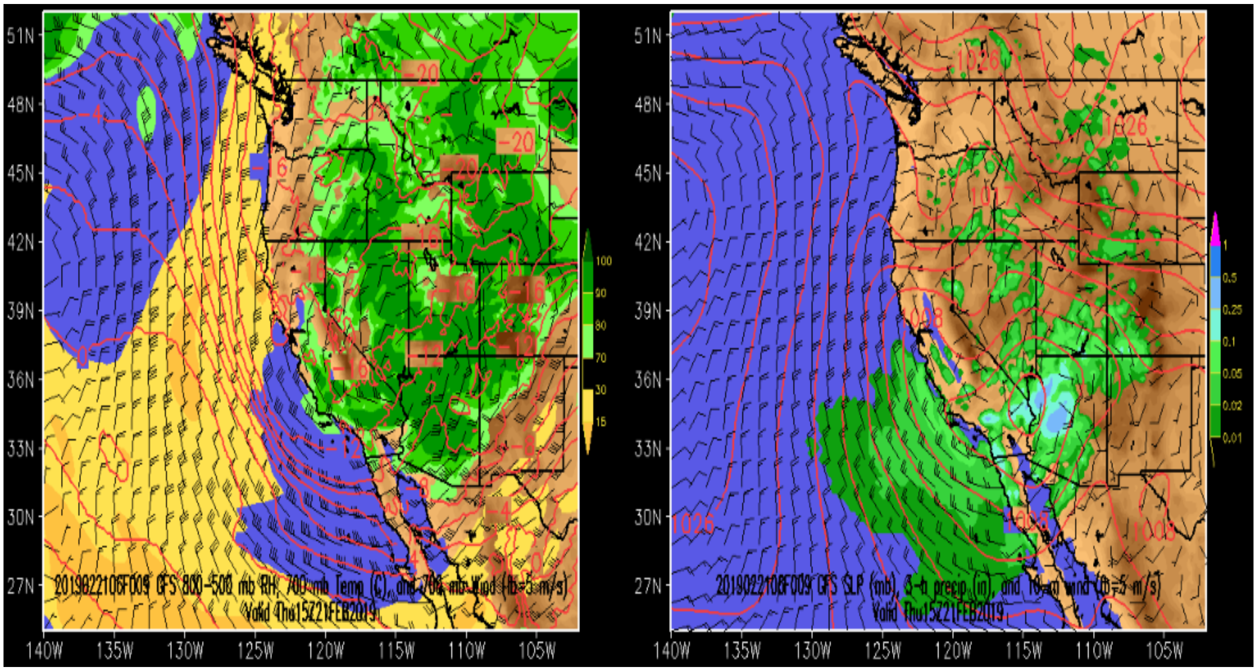

Figure 4.5 GFS Model Forecast during a Storm Event on February 21, 2019

A more recent product to which NAWC obtained access provides the ability to display a special High-Resolution Rapid Refresh (HRRR) model in support of operations. The software used by NAWC was developed by Idaho Power Company in support of their cloud seeding operations primarily by providing HRRR model analyses and forecasts of supercooled liquid water, temperature, moisture, and other parameters relevant to operations. Supercooled (colder than freezing) liquid water is the target of winter cloud seeding operations. More specifically, supercooled cloud liquid water at temperatures of -5˚C or colder is the target of operations, since silver iodide nuclei begin to become effective freezing nuclei at this temperature. The HRRR model does not forecast seeding effects, or the dispersion of seeding material such as does the HYSPLIT model, but it contains important atmospheric parameters in much higher time and space resolution than other (e.g. global) weather forecast models. Appendix B contains more specific information about modeling capabilities in support of the program.

An example of HRRR products is shown in Figure 4.6, generated using the script developed by Idaho Power, for an April 10 seeded storm period in northern Utah. In this particular plot, Vertically Integrated Liquid (VIL) is shown in the upper panel, which also displays the location of a vertical cross section as shown in the lower panel. This panel indicates that supercooled liqiuid water was predicted by the model at temperatures colder than -5˚C, the threshold activation temperature of silver iodide.

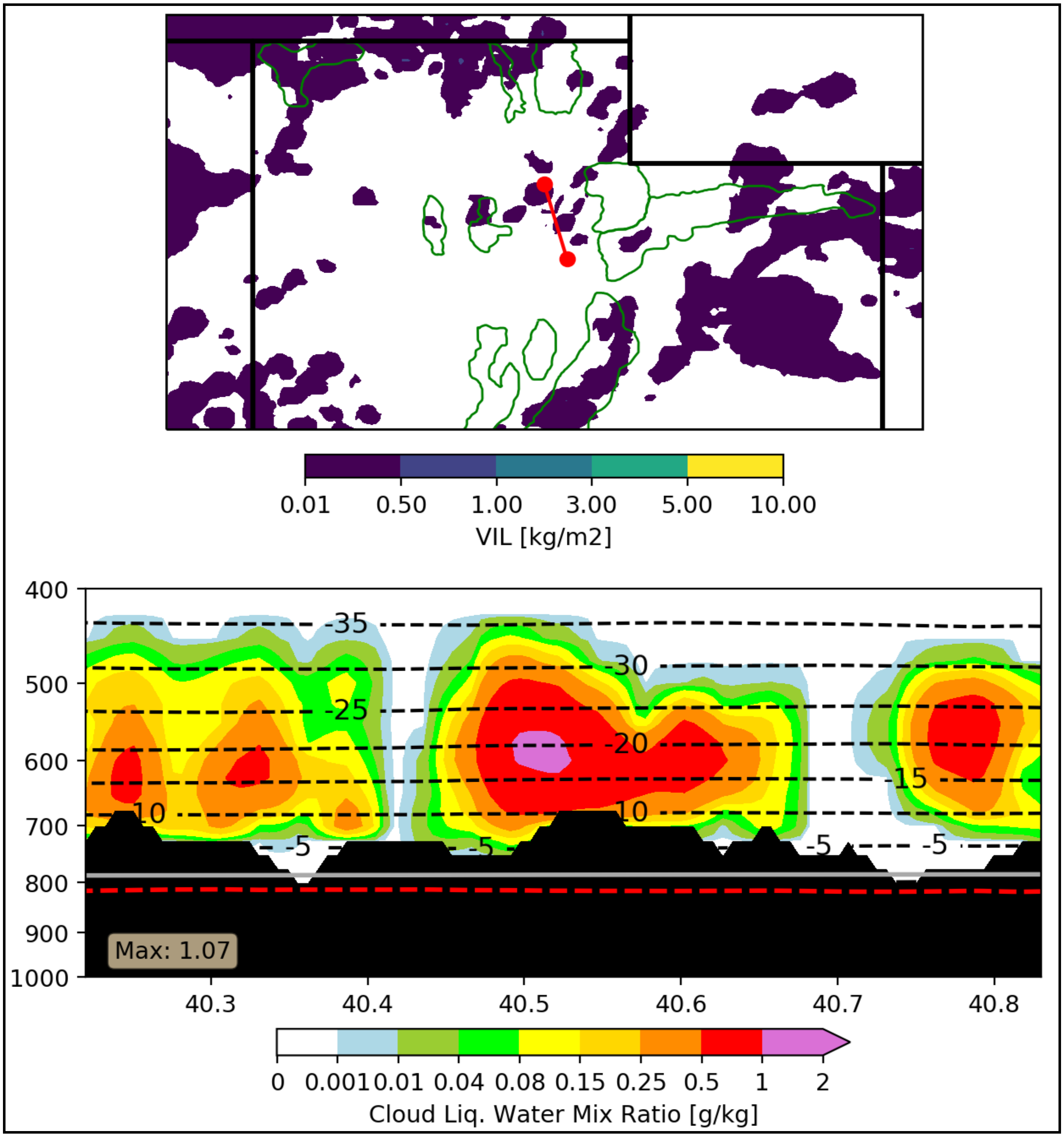

Figure 4.6 Liquid Water Forecast from the HRRR model in-house script during the February 5, 2019 storm event

5.0 OPERATIONS

This season's cloud seeding program for Six Creeks target area began on December 21, 2018 and ended on April 18, 2019. A total of 20 storm events were seeded during all or portions of 32 days. Three of these events occurred in December, three in January, four in February, six in March and two additional seeding events in April. A 1270.75 cumulative hours of seeding generator operations were conducted during the season from the ground sites. Table 5-1 provides the dates and ground generator usage for the season. Table 5-2 provides the hours of generator operations by generator site location. Seeding suspensions were enacted during the last week of April for the target area as snow water equivalent (SWE) values exceeded thresholds.

Table 5-1
Storm Dates and Generator Usage, 2018-2019 Winter Season

Storm Number	Date(s)	Number of CNGs Operated	Generator Hours
1	December 21, 2018	4	51.5
2	December 25, 2018	5	73.5
3	December 30-31, 2018	6	82.75
4	January 6, 2019	7	37.25
5	January 7, 2019	8	61.5
6	January 17-18, 2019	8	113.75
7	January 21, 2019	4	23
8	February 3, 2019	2	10.75
9	February 4-6, 2019	5	159
10	February 10, 2019	2	5.75
11	February 15-16, 2019	6	62
12	February 28, 2019	4	21.25
13	March 6-7, 2019	5	23.75
14	March 8, 2019	3	25.5
15	March 12-13, 2019	5	91.5
16	March 21-22, 2019	3	23
17	March 23-24, 2019	5	52
18	March 28-29, 2019	8	167
19	April 9-11, 2019	7	142
20	April 12, 2019	8	46.5

Storm Number	Date(s)	Number of CNGs Operated	Generator Hours
Total	---	---	**1270.25**

Table 5-2a
Generator Hours for 2018-2019, Storms 1-12

Storm	1	2	3	4	5	6	7	8	9	10	11	12
Date	**Dec. 21**	**Dec. 25**	**Dec. 30-31**	**Jan. 6**	**Jan. 7**	**Jan. 17-18**	**Jan. 21**	**Feb. 3**	**Feb. 4-6**	**Feb. 10**	**Feb. 15-16**	**Feb. 28**
SITE												
Baskin Reservoir	0	0	15.25	5.25	9.5	17.75	3.5	0	34	0	13.75	0
Mountain Dell Treatment	12.5	12	16	5.25	9.5	7	4.25	0	0	2.5	14	0
4500 S Pump House	0	0	15.25	5.5	9.5	18	3.5	0	34	0	13.25	0
White Reservoir	0	0	15.25	5.25	9.5	18	0	0	34	0	0	0
Big Cottonwood Treatment	12.5	14.75	15.5	5.5	9.5	18.25	6	3.25	29.25	0	13.75	0
Little Cottonwood Treatment	13	15	5.5	0	0	11	0	0	0	0	0	5
Wasatch Resort	13.5	15.75	0	5.25	0	17.75	5.75	0	0	3.25	13.5	6
Metro Treatment Plant	0	16	0	5.25	0	6	0	0	0	0	14.75	4.75
Alpine	0	0	0	0	0	0	0	7.5	27.75	0	0	5.5
Total	51.5	73.5	82.75	37.25	61.5	113.75	23	10.75	159	5.75	62	21.5

Table 5-2b
Generator Hours for 2018-2019, Storms 1-12

Storm	13	14	15	16	17	18	19	20
Date	Mar. 6-7	Mar. 8	Mar. 12-13	Mar. 21-22	Mar. 23-24	Mar. 28-29	Apr. 9-11	Apr. 12
SITE								
Baskin Reservoir	2	0	17.25	0	0	24	32.5	4
Mountain Dell Treatment	0	7.75	18	0	0	24	32.75	7.25
4500 S Pump House	2	0	18.75	0	0	28	32.5	4
White Reservoir	2	0	0	0	0	28	0	3
Big Cottonwood Treatment	2.75	10.75	18	0	8.25	24	15.5	7.25
Little Cottonwood Treatment	2	0	0	0	8.5	9.75	4.25	6.5
Wasatch Resort	13	0	0	0	8.75	5.25	20	7.5
Metro Treatment Plant	0	7	19.5	0	7.25	24	4.5	7
Alpine	0	0	0	0	19.25	0	0	0
Total	23.75	25.5	91.5	23 from additional sites*	52	167	142	46.5

***Seeding occurred from the High Uintas Project were used during this event, as southeastly flow allowed for targeting from these sites.**

Snowfall for the 2018-2019 winter season was well above normal for all of the target area and most of northern Utah. The higher SWE values seemed to favor the northern parts of the target area, with Louis Meadow consistently showing the largest above normal SWE values. As of April 8, 2019 SNOTEL, sites in the Six Creeks target area reported snowpack water content ranging from about 138% to 227% of the median, with an overall basin value of 170% of the median snowpack. The breakdown for each SNOTEL site is provided in Table 5-3. This table demonstrates that the 2019 Water Year was abnormally wet. The reason for the differences between median snow water equivalent percentage and precipitation percent of average values is unknown.

Table 5-3
Snowpack and Precipitation Data from SNOTEL sites – April 8, 2019

Site	Snow Water Equivalent (inches)	Median Snow Water Equivalent (inches)	Snow Water % of Median	Water Year Precipitation (inches)	Water Year Precipitation Average	Water year Precipitation % of Average
Louis Meadows	25.6	12.6	203%	38.9	28.8	135%
Lookout Peak	38.0	24.2	157%	44.3	33.4	133%
Parleys Summit	21.3	9.4	227%	31.1	23.7	131%
Mill-D North	36.7	21.9	168%	36.2	28.9	125%
Brighton	36.1	22.7	159%	39.2	28.9	136%
Snowbird	56.6	40.9	138%	50.0	40.0	125%
Basin Index			**170%**			**134%**

Monthly snow water equivalent maps for the season are shown in Figures 5.1 to 5.4. Figures 5.5 to 5.7 show plots of data from three SNOTEL sites located in the target area during the 2018-2019 winter season. April seemed to be the wettest month, in terms of SWE and precipitation, with locations in the target exceeding SWE values of over 200% at more than one location.

Figure 5.8 shows the seasonal snow water equivalent time series data for the Provo-Utah-Jordan Basin as a whole compared to average values and some recent winter seasons.

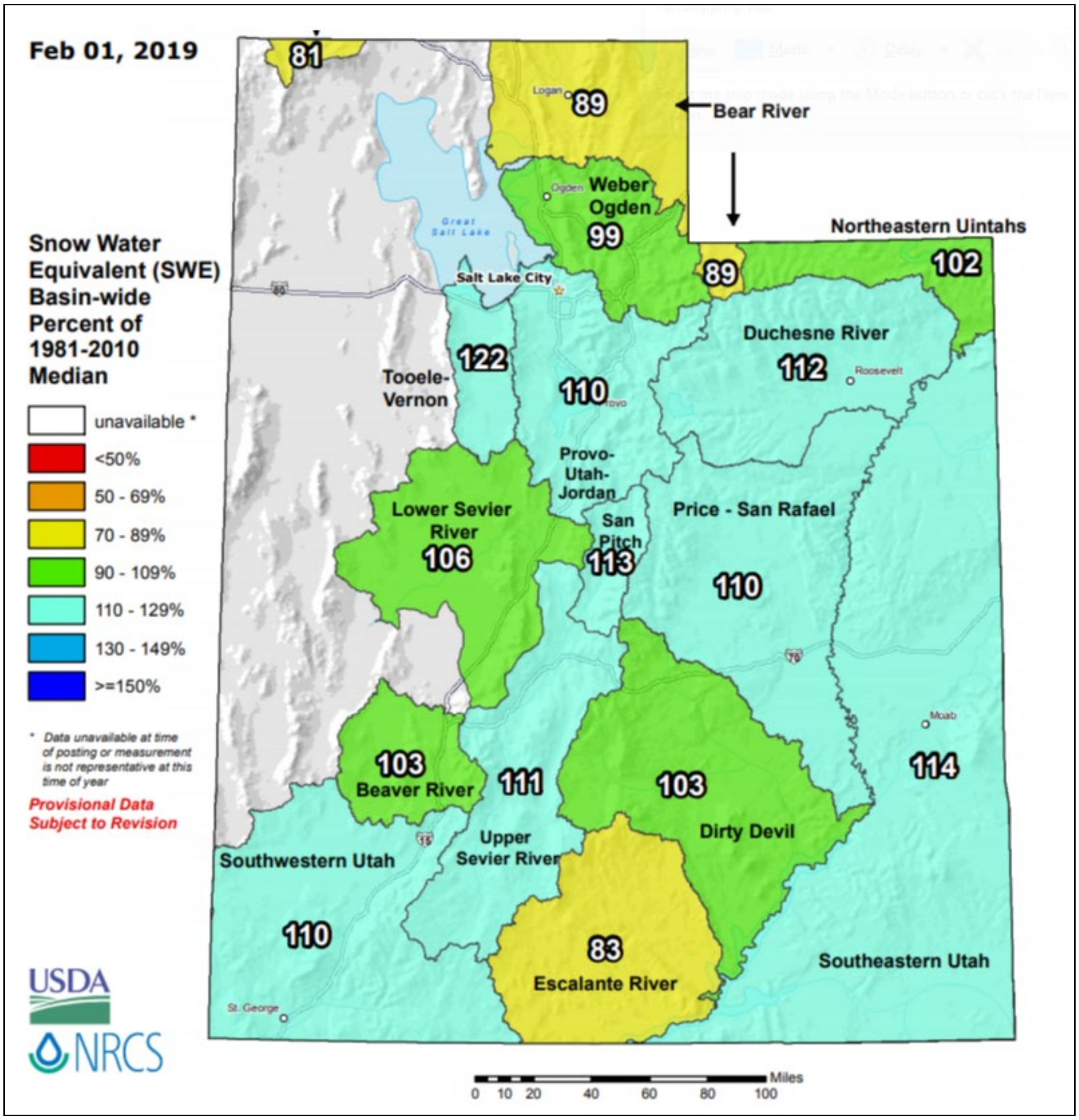

Figure 5.1 January 2019 Snow Water Equivalent, expressed as a percent of median

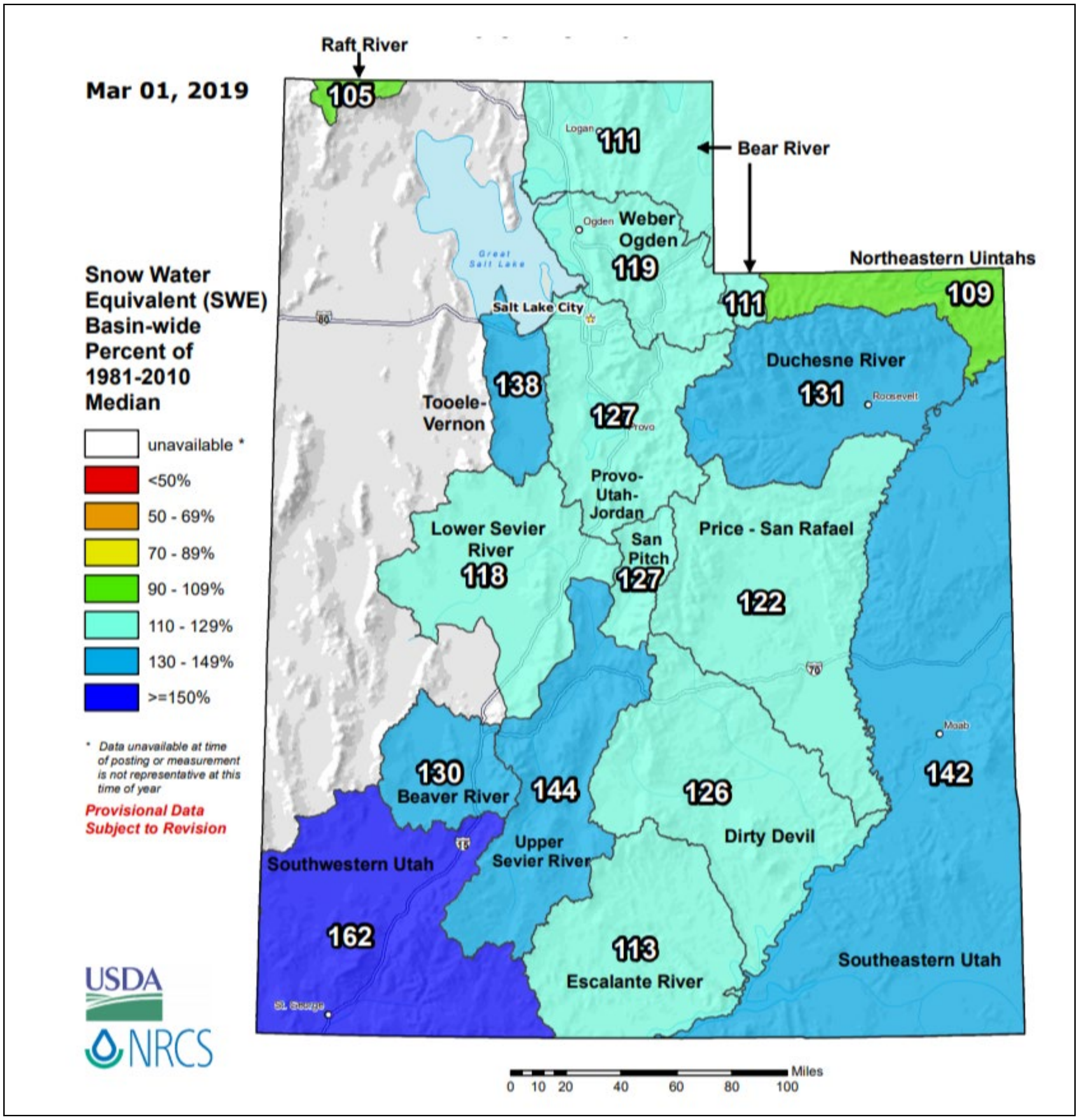

Figure 5.2 February 2019 Snow Water Equivalent, expressed as a percent of median

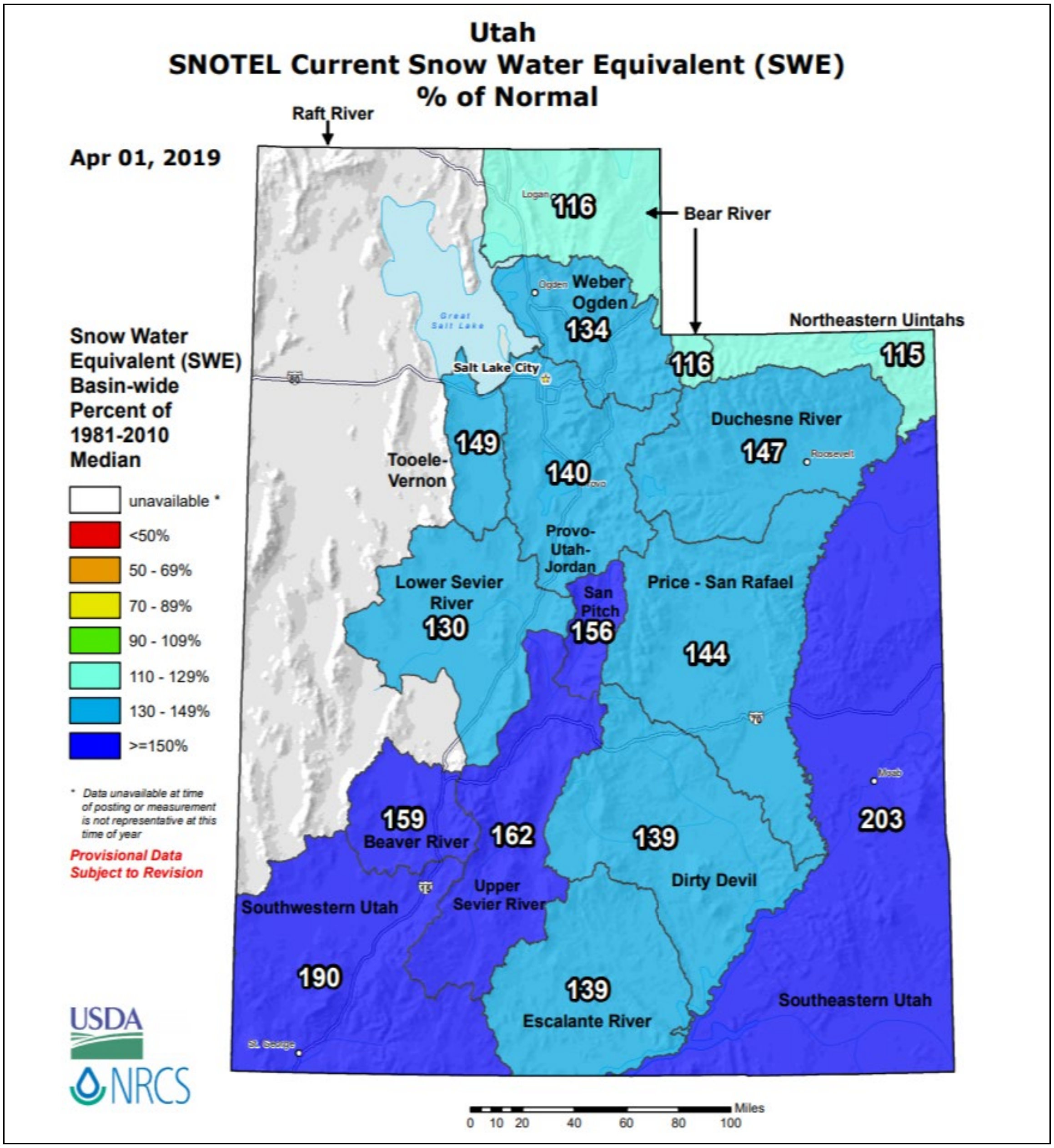

Figure 5.3 March 2019 Snow Water Equivalent, expressed as a percent of median

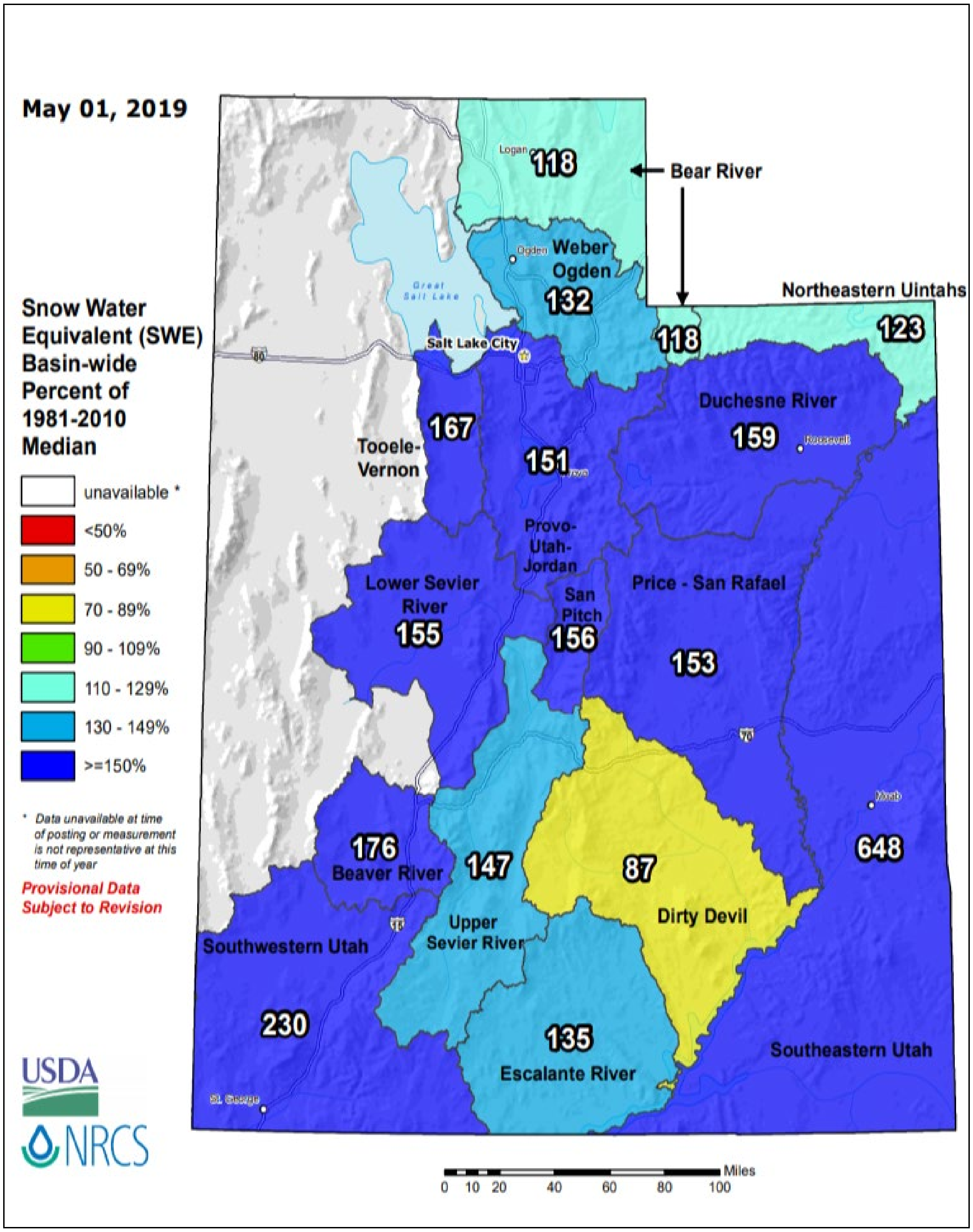

Figure 5.4 April 2019 Snow Water Equivalent, expressed as a percent of median

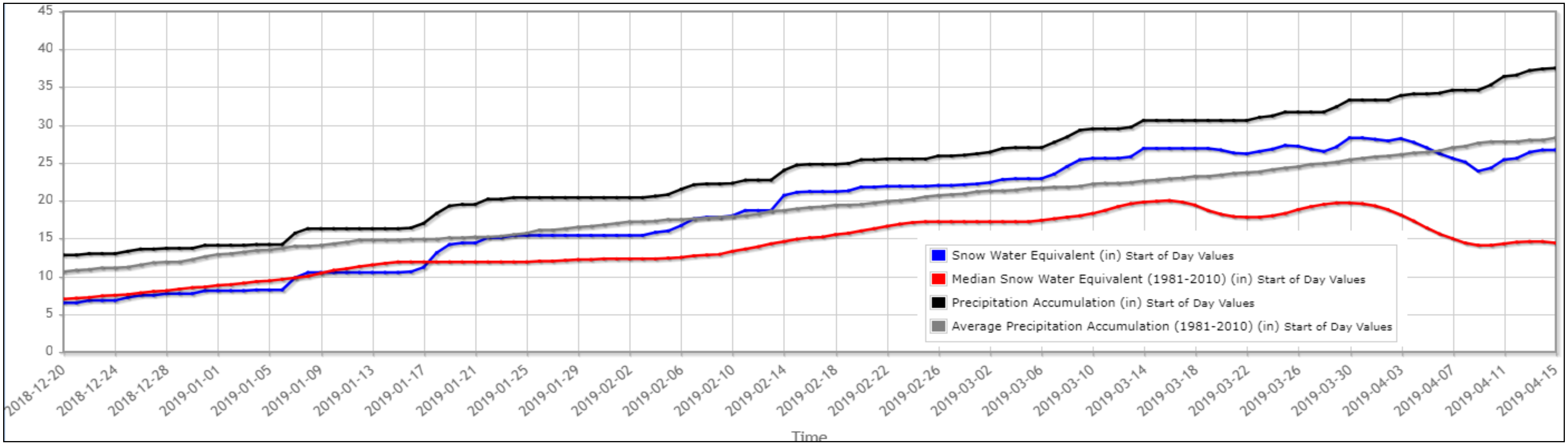

Figure 5.5 NRCS SNOTEL snow and precipitation plot for December 20, 2018 through April 15, 2019 for Louis Meadows

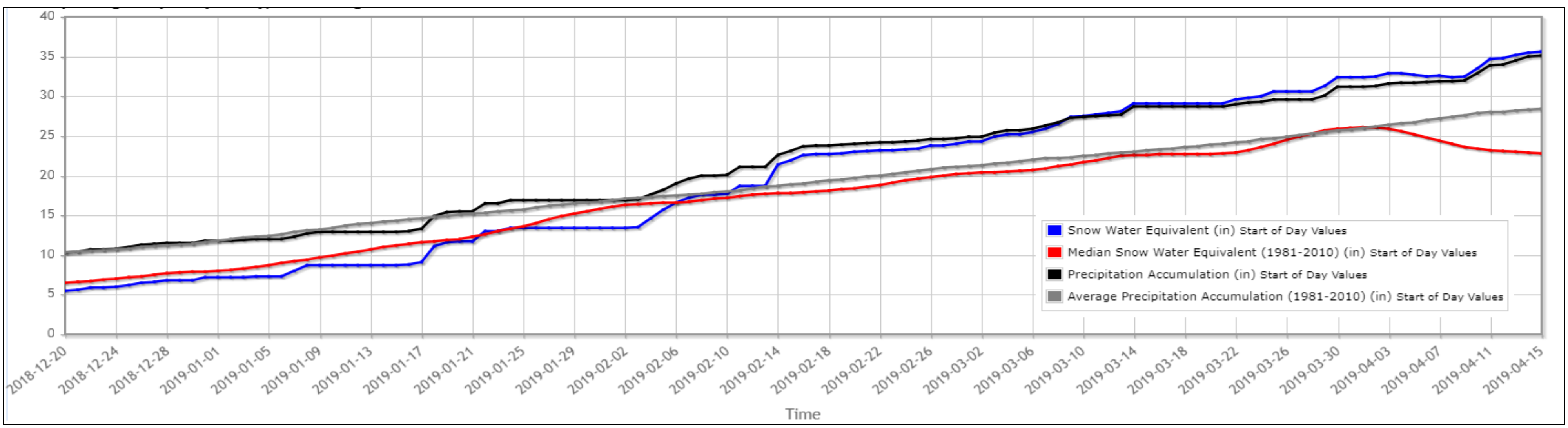

Figure 5.6 NRCS SNOTEL snow and precipitation plot for December 20, 2018 through April 15, 2019 for Mill D - North

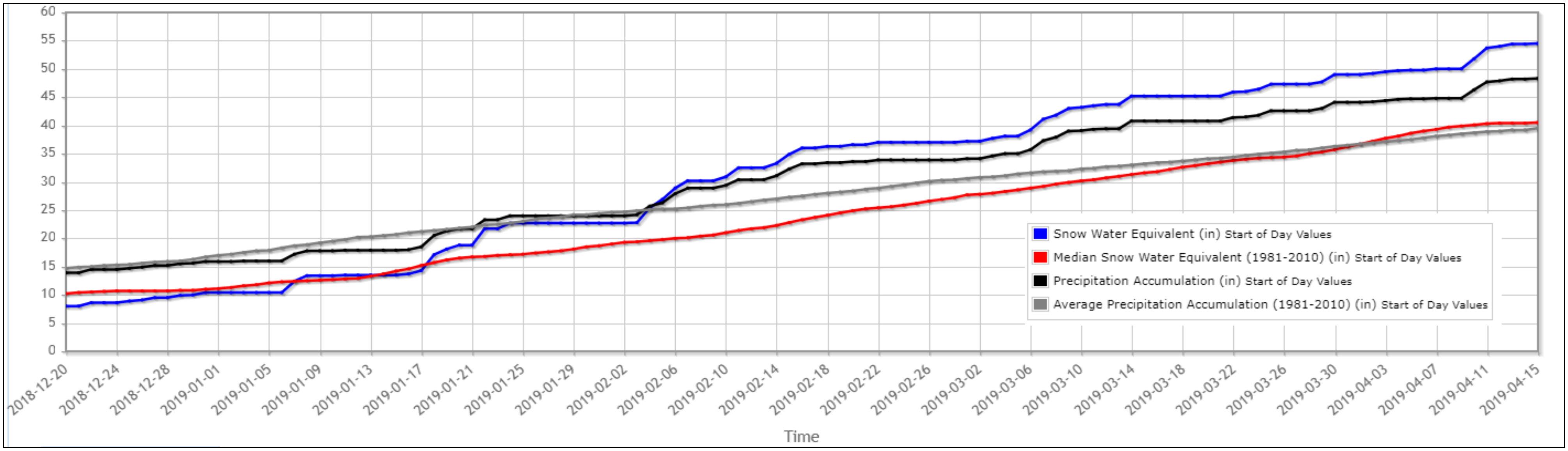

Figure 5.7 NRCS SNOTEL snow and precipitation plot for November 15, 2018 through April 15, 2019 for Snowbird

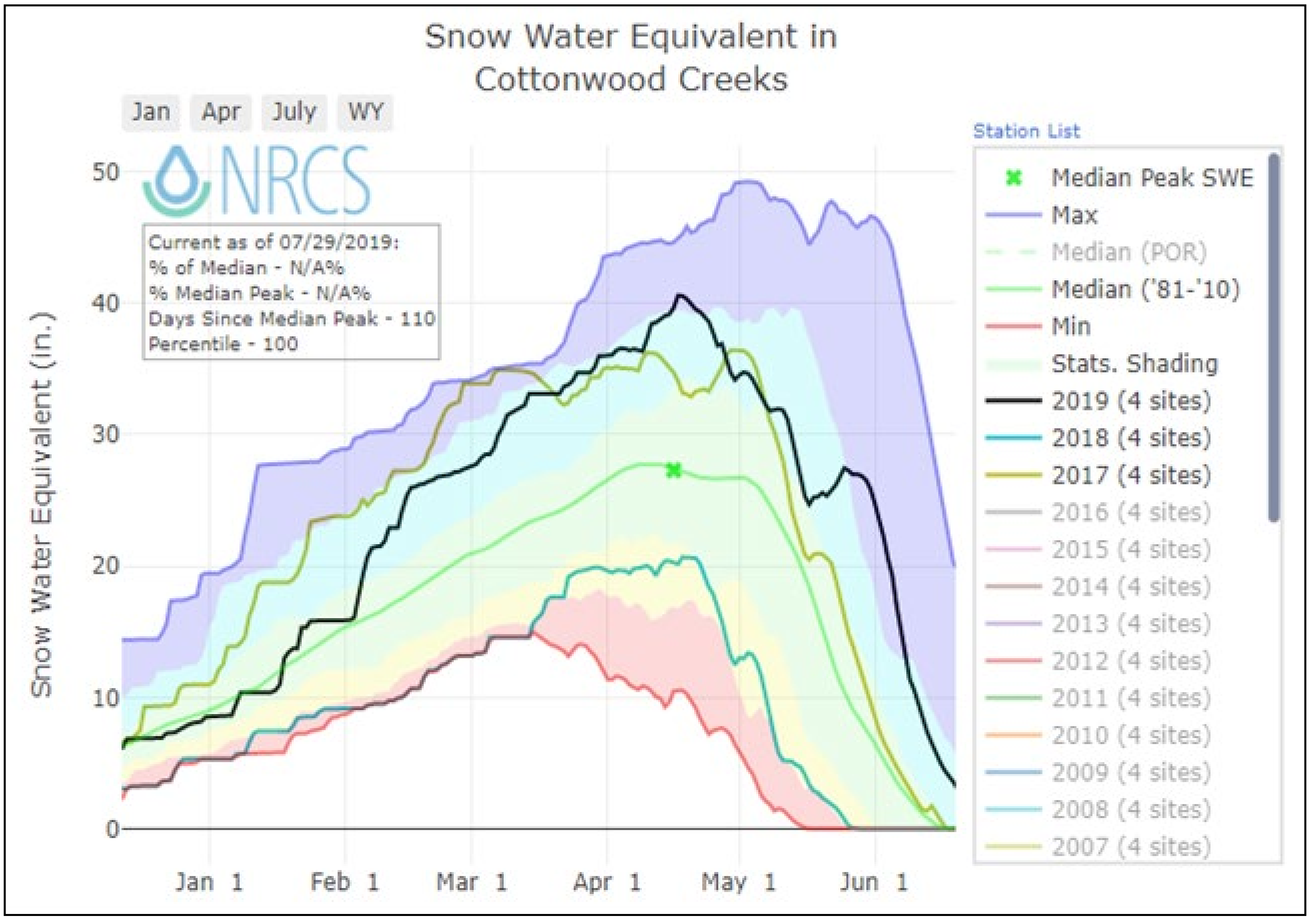

Figure 5.8 Cottonwood Creeks Snow Water Equivalent values – 2017-2019 with Median SWE values

5.1 Operational Procedures

In operational practice, an approaching storm was monitored at the NAWC operations center at NAWC's corporate offices located in Sandy, Utah utilizing online weather information. If the storm met the "seedability" criteria presented in Table 2-1, and if no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators were activated and adjusted as conditions required. Seeding continued as long as conditions were favorable and seedable clouds remained over the target area. In a normal sequence of events, certain generators would be used in the early period of storm passage, some of which might be turned off as the wind direction changed, with other generators then used to target the area in response to the evolving wind pattern. The wind directions during productive storm periods in the Six Creeks target area usually favor a northwesterly or southwesterly direction (in meteorology wind direction is reported in terms of the direction from which the wind is blowing).

5.2 Operational Summary

This section summarizes the weather conditions and seeding operations during storm events. All times are local (MST/MDT) unless otherwise noted. Recall when wind directions are provided these directions are reported from the direction the wind is blowing from (i.e. a northwest wind would be blowing towards the southeast).

December 2018

December brought drier conditions, but still near normal SWE and precipitation values to the Six Creeks target area. The month also brought three moderately strong storms during which seeding operations were conducted.

On the 21st, showers moved into the area from the west, as a moderately strong wave affected the Wasatch during the evening hours. Temperatures were somewhat warm to begin with but did cool as precipitation started over the area. Wind observations were a little chaotic at the surface but 700 mb observations showed westerly winds in place. Seeding operations began around 1830 MST and continued into the morning hours. Seeding operations ended as precipitation ended during the early morning hours of the 22nd.

An area of low pressure moved into Utah from California on the 25th, which led a chance for seeding operations. Winds were southerly as seeding began but became more northwesterly overnight as the trough axis associated with the aforementioned area low pressure moved through the region. Temperatures were around -6°C at 700 mb when seeding began but continued to drop as cold air advection from the west cooled the atmospheric column. Seeding operations ended between 0930 MST and 1030 MST on the 26th as precipitation ended at that time. Scattered showers occurred later in the day but amounts were minimal.

A strong cold front moved into the target area on the 30th, with seeding operations initiated with northwesterly flow in place and 700 mb temperatures around -8°C. Seeding operations continued overnight but ended early in the morning on the 31st, as precipitation continued across most of the target area but temperatures dropped to -15°C at 700 mb, which according to NAWC's seeding criteria, are deemed too cold for seeding operations as little to no liquid water is likely to be present.

January 2019

January proved to be a fairly active month for the Six Creeks target area, as a number of seeding opportunities occurred during the first and middle parts of the month. There were a few storms that occurred that were not seeded due to stability issues, which is fairly common in Utah during the month of January, when inversions are more prevalent than other months of the year. Low-level inversions can trap seeding material in lower elevations rendering seeding ineffective.

Heavy snowfall started between 1000 and 1100 MST on the 6th. This led to the initiation of seeding operations, as southwesterly flow and temperatures of around -6°C at 700 mb lead to suitable conditions. This first wave ended around 1500 MST, as a trough axis moved through the Salt Lake Valley resulting in rapid clearing. Consequently, seeding operations were discontinued around 1500 MST.

Precipitation developed once again as a cold front moved across the Salt Lake City valley on the 7th. Pre-frontal moisture and winds were conducive for seeding operations over most of the Six Creeks target area. A strong fontal band of snowfall occurred between 1200-1300 MST, with continual post-frontal precipitation occurring throughout the afternoon. Seeding operations were concluded around 1600 MST, as precipitation ended with drier air filtering into the area behind the departing trough/front.

Moisture increased over the target area as a weak system moving from southern California and Arizona, moved into Utah on the 16th, allowing for suitable seeding conditions to develop on the 17th. Low-level stability hindered operations from occurring on the 16th, with 700 mb temperatures remained around -5°C during the overnight and morning hours. Precipitation became more convective during the afternoon hours with widespread moderate to heavy precipitation. Winds initially were southeasterly, which is a difficult wind regime to target the seeding effects, however, northwesterly flow occurred overnight with cooler temperatures. Seeding occurred during the late evening to overnight hours, with some seeding sites turned off in the early morning hours with northerly flow in place. A few sites remained active until around 1400 MST on the 18th, as precipitation ended in most locations. This storm brought heavy snowfall to most of the Wasatch, with 2-3 feet of snow recorded at many of the ski areas and 2-3 inches of snow water equivalent (SWE) observed at target area SNOTEL sites.

A strong trough pushed through the target area early on the 21st. Precipitation began overnight, initially further north of the target area precipitation, beginning around 0500 MST in the Salt Lake Valley. Temperatures were rather warm to begin with, around -4°C at 700 mb. Operations did not begin until around 0830 MST as winds became more favorable, which had been rather light earlier that morning. Temperatures also became more favorable as colder air began to filter into the region. Seeding continued into the early afternoon hours when precipitation began to decrease in coverage and intensity.

February 2019

Another active month occurred in February, with seeding operations occurring mainly during the first couple of weeks of the month and one additional seeding day near the end of the month. After the 16th, strong high pressure built into the area, yielding very cold temperatures and very dry conditions across most of the northern half of the state.

Rain and snow showers were ongoing during the morning of the 3rd, with temperatures a bit too warm to conduct seeding operations as of 0800 MST. 700 mb temperatures cooled as the day went on and by 1100 MST, operations were initiated with winds becoming favorable as well. Seeding operations were terminated later in the day as precipitation ended but increased overnight and into the morning hours of the 4th.

Pre-trough/frontal precipitation continued on the 4th with mostly light amounts observed. Seeding operations did occur from one site in the southern part of the target area as southerly winds helped to transport seeding material upward. Seeding from this site continued all day and into the next morning, the 5th, when additional sites were added, as winds remained southwesterly before the frontal passage moved through the Salt Lake Valley during the afternoon hours. The surface front allowed for northwestly flow and temperatures to decrease to around -8°C over the region for the duration of the event. A lake effect band set up over the area on the 6th, when seeding operations were already occurring, mostly targeting the Cottonwoods and Oquirrh mountains. Temperatures on the 6th at 700 mb dropped to -12°C with snowfall continuing throughout the day. Seeding operations were finally terminated around 1500 MST when precipitation started to decrease and temperatures continued to drop.

A strong cold front moved through the Salt Lake Valley during the evening hours of the 10th, with a very pronounced precipitation band on radar. Winds were southwesterly at the surface but quickly became northwesterly as the cold front allowed for colder air in the move into the region. Temperatures were around -8°C and continued to fall throughout the evening hours. Seeding operations occurred into the late evening hours with temperatures to the north of the area dropping to -18°C at 700-mb.

A warm rain event occurred overnight from the 14th into the 15th, with 700 mb temperatures around -3°C, which were too warm for seeding. However, a front moved through the area on the 15th and allowed for a period of moderate snowfall to occur for the target area after 1830 MST. Seeding operations began around this time, with some convective echoes observed on radar. The warmer air mass was replaced with a colder one, with temperatures around -9° C. Operations continued throughout the evening hours into the morning of the 16th, when 700 mb temperatures at Salt Lake City were observed at -14°C, which signaled the end of seeding operations for this event.

A weak trough moved through the state on the 28th, which produced convective rain and snow showers throughout the day. 700 mb temperatures were around -4°C and winds were southwesterly, but with convective snow showers observed, this made seeding at warmer temperatures suitable with the additional lift provided from the convection. Seeding occurred throughout most of the day with operations concluding around 1900 MST as activity began to diminish. Snowfall amounts of 3 to 7 inches were reported in the Wasatch.

March 2019

March was the most active cloud seeding month for the Six Creeks project as a number of storms with very suitable conditions for seeding impacted the area. Activity was somewhat slow early in the month, but quickly picked up near the middle of the month.

On the 6th, a subtropical plume of moisture moved into the state of Utah. Temperatures associated with this plume of moisture ranged between -3° and -4°C. Some convective echoes were noted on radar. One site was activated in southerly flow. Seeding with this site continued overnight and on the morning of the 7th, additional sites were added as conditions became more favorable. Operations began around 0800 MST and ended around 1300 MST, as clearing began to occur over the target area.

A large trough was centered over the Great Basin on the 8th, with precipitation increasing over the target area during the morning hours. 700 mb temperatures were between -5° and -6°C, with winds generally southeasterly early in the day with a gradual shift to the southwest as the trough progressed. Numerous sites were activated as winds became westerly/southwesterly around 1100 MST. A well-defined frontal band moved through the area with embedded convection around 1500 MST, as northwest flow developed. Snowfall continued throughout the day and into the early evening hours. A general decrease in precipitation was noted later in the evening and seeding operations were terminated.

An upper level trough was located to the north, which helped to bring northwesterly flow in the upper levels on the 12th. Additionally, a strong trough to the southwest was also contributing to moisture advection into the area. Temperatures at 700 mb were somewhat marginal, but a number of seeding sites were activated during this event, with good convective activity and cold air advection. Seeding continued throughout the day and into the 13th, as moderate snowfall continued through midday. Operations were concluded between 1400 and 1500 MDT, as precipitation ended.

A trough moved into the southwestern U.S on the 21st, when a rapid transition from a dry atmosphere to a significant precipitation event occurred early in the morning. Initially, precipitation occurred from a higher deck with 700 mb temperatures between -4° and -5°C. Winds throughout the event remained from a southeasterly direction, a direction not seedable from the Six Creek's generator network. However, seeding sites east of the Wasatch Front, near Midway, Heber and Wallsburg were used to seed the target area. Seeding began around 2000 MDT and continued through the overnight hours. Seeding operations ended around 0800 MDT, as precipitation began to diminish.

Weak convective shower developed over portions of northern Utah on the 23rd, with widely scattered showers over the Six Creeks project area throughout most of the day. Temperatures at 700 mb were around -4°C, with light winds from the south. Seeding operations around 2000 MST from the Alpine site as precipitation occurred during the overnight hours. The light winds and the southerly component rendered other sites in affecting the target area. By the morning of the 24th, widespread snow and rain was occurring over all of the Salt Lake Valley, with 700 mb temperatures around -7°C. Additional sites were activated at this time, mainly for the southern half of the target area. Winds were generally southwesterly at the surface. Seeding operations ended around 1630 MDT as precipitation generally diminished.

A weak post-frontal trough was located over the Salt Lake Valley on the 28th, with increasing activity to the west around 1600 MST with the approach of a potent upper level area of low pressure. Temperatures were warming at the surface and cooling aloft, leading to convective showers developing. A number of sites were activated, with additional sites being activated around 2000 MDT. Operations occurred throughout the evening hours into the 29th. A lake effect band developed during the evening centered over the Cottonwood Canyons. 700 mb temperatures remained cool with -8°C observed at 700 mb and cooler air noted over Nevada that later moved into northern Utah. All of the ski resorts in the Cottonwood Canyons received between 10 and 12 inches of snowfall overnight from the 28th to the 29th. Northwesterly flow is typically very beneficial for these areas during storm events.

April 2019

April proved to be another wet month for the target area, along with somewhat significant April storm that affected the area between the 9th and 11th. Seeding operations ended before the 15th for the season due to above normal SWE values.

A large-scale trough moved through and surface cold front moved into the Great Basin on the 9th. 700 mb temperatures were rather warm but cooled to -5°C later in the day. Light orographic precipitation began later in the day, which led to the activation of one seeding site. Precipitation became more widespread and heavier on the morning of the 10th, with almost all seeding sites being activated. Surface winds at all locations indicated good upslope flow, which allowed for the transport of seeding material into the target area. Orographic continued throughout most of the day, which allowed convective type showers to develop. Winds were rather strong at the 700 mb level from the southwest, with some lake effect precipitation occurring during the evening hours from the 10th into the 11th. Temperatures through the event at 700 mb ranged between -8° to -9°C. A few additional sites were added on the morning of the 10th, around 1145 MST, and seeding continued throughout the day and ended around 1600 MST, when precipitation began to decrease across the Salt Lake Valley.

Early lake effect snow and low based convective snow showers on the 12th, resulted in one last day of seeding operations to the 2018-2019 season. Northwesterly flow also aided an orographic effect, which led to moderate snowfall throughout the day. 700 mb temperatures remained around -8°C for the storm event. Seeding continued from a number of sites throughout the day and ended around 1900 MST as snow showers began to taper off with the loss of daytime heating.

6.0 ASSESSMENT OF SEEDING EFFECTS

6.1 Background

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 percent for individual seasons, and in the range of 5-15 percent 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 for the Six Creeks program. 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 significant.

NAWC has used a commonly employed evaluation technique referred to as the "target and control comparison", 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 area consists of sites well correlated with the target area sites, but which would be unaffected by any seeding programs. 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 seeding impacts, which would 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% 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.

For the Six Creeks program, which was originally active in the late 1980s through mid 1990s, a target/control evaluation was developed in the early 1990s and used to estimate the seeding effects. The regression equation developed at that time utilized precipitation data from various sources. This was before a significant SNOTEL data climatology was available, as most of the SNOTEL sites were installed in the late 1980s in this area, with the earliest sites being installed in the late 1970s. Most of the other types of precipitation gages used in the early analysis are no longer consistently active, or have poor data availability (e.g. data gaps) compared to SNOTEL data which normally has no missing data. Additionally, lower elevation precipitation sites have poorer correlation to the higher elevations of the seeding target area than do similar high-elevation (i.e. SNOTEL) control sites. Therefore, the various recently developed target/control analyses for this program, which can be applied to the 2019 season (and to any future seeded seasons), are based solely on SNOTEL data. The historical regression period of 22 years, consists of the non-seeded water years of 1997-2018, which is considered an adequate base period. The earlier seeded seasons of 1988-1996 can be used as an external data set for these new evaluations, which can be used for some statistical measures that help to gauge the usefulness of a particular equation.

6.2 Evaluation Approach

The state of Utah (as well as many other westerns states) has an excellent SNOTEL data collection system. These automated sites collect both cumulative precipitation and snow water content data. Precipitation and snowpack data used in these analyses were obtained from Natural Resources Conservation Service (NRCS) SNOTEL sites and are publicly available online. For evaluation of a seeding program, the precipitation data are typically summed over a representative season (for example, November – April or December – March) which can be used consistently in the evaluation, even though the seasonal period of seeding operations may potentially vary somewhat from one season to another. April 1 snow water equivalent (SWE) measurements are hydrologically strategic and have typically been used for the snowpack portion of the seeding evaluations, since at high elevation sites the April 1 SWE frequently represents the approximate maximum snow accumulation for the winter season. Most streamflow and reservoir storage forecasts are also made by state water agencies based on the April 1 snowpack data.

Some potential pitfalls with snowpack measurements must be recognized when using snow water content to evaluate seeding effectiveness. One potential problem is that not all winter storms are cold, and sometimes rain falls in the mountains. At some lower elevation mountain sites this can lead to a disparity between precipitation totals (which include all precipitation that falls) and snowpack water content (which includes only the water content of the snowpack at a particular time). In addition, warm periods can cause some melting of the snowpack prior to April 1. If the melting is sufficient, the water content in the snow can be lower than the total amount, which actually fell. Additionally, not all storms that produce snow in the higher elevation areas of Utah are seeded (e.g., in this case, prior to December 15th). Since the April 1st snow water content usually represents total seasonal snowpack accumulation, the apparent results of a seeding program conducted for a portion of the accumulation season will be less (in terms of the percentage increase) than if only the seeded period was evaluated.

In evaluating the SNOTEL site data, double-mass plots were produced as a quality control measure. These are a special type of scatterplot of cumulative data over a time period in questions, allowing a chronological comparison of two sites, or a site vs. a group data mean, etc. The purpose is to test for outliers in the data or long-term changes in the relationships between sites, which would negatively affect a target/control evaluation. In some cases, sites, which appear to be outliers in this way, may be excluded from the analyses. For these equations, potential target and control sites were compared in this way for the non-seeded seasons. In general, the data were in good agreement for both precipitation and snowpack during these seasons. However, one potential control site (Timpanogos Divide), which is just south of the Six Creeks target area, had data that varied somewhat from that of most other sites during certain time periods. The location of this particular site also suggests that, although technically outside of the target area, it is likely to receive substantial seeding effects in northwesterly wind patterns. Due to these factors, a decision was made to exclude it as a control site.

6.3 Target and Control Data Resulting Equations

The precipitation evaluation equations utilize SNOTEL data summed over both the November – April and December – March seasonal periods. This allows some flexibility in focusing the precipitation analysis on the seasonal periods when seeding actually takes place, if the program is active in future seasons. The snowpack (SWE) equations utilize April 1 data, although data from other dates could be selected (which would require the development of new regression equations). April 1 SWE may include snow that accumulated before seeding began in a particular season, and would exclude the effects of any seeding after April 1, etc. In some seasons, snowmelt prior to April 1 may also affect the SWE analyses to an extent. For these reasons, the SWE equations have slightly lower correlations (r values) and the results may be inferior to those produced by the corresponding precipitation analyses.

Figure 6.1 shows a map of the target area and the six target SNOTEL sites, while Figure 6.2 is a more zoomed out image showing locations of the three control sites in relation to the target area. Location and elevation information for these sites is provided in Table 6-1. The six SNOTEL sites selected within the seeding target area should represent this area well in terms of their geographic locations and the potential to quantify seeding effects. The three control sites were selected based on the desire to bracket the target area geographically, especially in the north-south dimension. This helps to account for storm track variations and to avoid cross seeding effects on other seeding programs at the control sites. This is a challenging task, due to the number of seeding programs in Utah. A site north of the target area (Farmington Upper SNOTEL) and a couple of sites in eastern/northern Nevada, Berry Creek and Pole Creek, were selected as controls. These two Nevada sites are also utilized as controls for other Utah seeding programs. A SNOTEL site called Cascade, somewhat to the south of Timpanogos, was analyzed as a potential control. However, that site had a shorter period of record, which begins in 2003. It also did not compare well to other sites in the area on a double-mass plot, with many seasonal and multi-seasonal variations in comparison to the other sites. The implication in the resulting equations is that this set of three control sites would be ideal for producing a realistic forecast of "natural" target area precipitation for comparison to the observed values during the seeded seasons. For the Six Creeks target area, sites that were inside the target area were utilized. Target sites include Lookout Peak which is near the northern boundary. Two other sites near the northern boundary, Louis Meadow and Hardscrabble, are not included to avoid overweighting this northern boundary area in the evaluations.

Figure 6.1 Six Creeks SNOTEL Target Site Locations (target area denoted in red)

Figure 6.2 Six Creeks SNOTEL Control Site Locations

Table 6-1
Target and Control SNOTEL Sites for Precipitation and Snowpack Evaluations

Site Name	Latitude	Longitude	Elevation (ft)
Target Sites			
Snowbird	40°34' N	111°40' W	9177
Brighton	40°36' N	111°35' W	8766
Mill-D North	40°40' N	111°38' W	8963
Parley's Summit	40°46' N	111°38' W	7585
Lookout Peak	40°50' N	111°43' W	8161
Control sites			
Farmington (Upper)	40°58' N	111°49' W	7902
Berry Creek, NV	39°19' N	114°37' W	9377
Pole Creek, NV	41°52' N	115°15' W	8360

The linear regression equation developed from the historical relationship etween 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:

$$SE = (Y_O - Y_C) / (Y_C * 100)$$

The regression equations and the historical correlation coefficients for the two target areas are presented in Table 6-2. The stations, which constitute each control/target group, are listed in Appendix C.

Table 6-2
Regression Equations and Coefficient/Variance for Precipitation and Snowpack Evaluations

Evaluation Type	Equation	Correlation Coefficient (r)	Variance (r^2)
Precipitation November-April Linear	$Y = 1.267(X) + 1.76$	0.932	0.868
Precipitation November-April Multiple Linear	$Y = 0.623(X_1) + 0.003\ (X_2) + 0.366(X_3) + 2.24$	0.959	0.920
Precipitation December-March Linear	$Y = 1.339(X) +0.37$	0.943	0.889
Precipitation December-March Multiple Linear	$Y = 0.588(X_1) + 0.014\ (X_2) + 0.546(X_3) +1.02$	0.958	0.917
Snow April 1 Linear	$Y = 1.131(X) – 2.35$	0.943	0.889
Snow April 1 Multiple Linear	$Y = 0.406(X_1) + 0.411\ (X_2) + 0.205\ (X_3) – 0.56$	0.946	0.895

Where:

Y = Calculated average target precipitation (November – April) or April 1stsnow water content.

X = control 3-site average, X_1 = Farmington, X_2 = Berry Creek, NV and X_3 = Pole Creek, NV

6.4 Results for the 2019 Water Year

Evaluation results for the 2019 water year were mixed when using these equations to predict the "natural" precipitation or snow for the target area in the absence of seeding, in comparison to the observed values. Results of the December – March precipitation and the April 1 snowpack evaluations are shown in Table 6-3. In this case, the November – April precipitation results were not included because there were no seeding operations until later in December. It is worth keeping in mind that single-season results have very little statistical significance, and multiple seasons are required to yield a stable result in these types of evaluations. This is due to a high natural variability in precipitation and snowfall patterns between control and target sites, compared to the effects of the seeding program. The precipitation evaluations generally yielded observed/predicted ratios close to (or just on either side of) 1.0 for this season, which is not suggestive of a seeding effect. The snowpack evaluations yielded much higher ratios than those for precipitation, with ratios of 1.17 and 1.16 for the linear and multiple linear respectively. These latter ratios are suggestive of increases of approximately 16-17% over the natural values, which could possibly be attributed to seeding.

It is not clear why there is a substantial difference between the precipitation and snowpack results for this past season, although this type of difference (varying in either direction) is sometimes observed in single-season results. This is a consequence of the fact that there are a number of extraneous factors that can affect the outcome of these evaluations, particularly on a single-season basis. The efficiency of precipitation gauges in catching snowfall is known to decrease (perhaps substantially) with increasing wind speed. The SWE measurements can also be affected by various factors, such as blowing snow or variations in snowmelt patterns during the season prior to April 1. The effect of any of these factors may vary from site to site and from season to season, which may affect the relationship between target and control data and thus the evaluation results.

In addition to the ratio of the observed to predicted values discussed above, the predicted values obtained in the regression equations can be subtracted from the corresponding observed values, to examine the difference in observed minus predicted values based on the target area average. When the observed/predicted ratio for a particular evaluation is less than 1.0, this value will be negative, and when the ratio is greater than 1.0 the value will be positive. When data from several or more seeded seasons are available, the composite observed minus predicted values based on multiple seasons of data can begin to indicate the magnitude of precipitation (or snow water content) increases that are likely being generated by the cloud seeding operations.

The bottom row in Table 6-3 summarizes the overall "mean" of these results, since the results shown here only cover one season of analysis. The data are not typically averaged in this way, but these mean values may aid in the interpretation of this season's mixed results from the different evaluation techniques. This overall mean result is a ratio of 1.08, which could be taken to suggest an 8% increase in precipitation/SWE. This ratio is equivalent to over 2 inches of additional precipitation/SWE for this particular season. A similar program was conducted for this Six Creek's target area for water years 1989 through 1996. The linear and multiple linear regression equations developed for the analysis were also applied to the historically seeded period of 1989-1996 water years (one or more of these SNOTEL sites did not have data available yet in 1988). For this set of years as a whole, December – March precipitation evaluation results averaged 1.05 (linear) and 1.06 (multiple linear). For April 1 SWE, results averaged 1.08 (linear) and 1.03 (multiple linear).

Table 6-3
Evaluation Results for the 2019 Water Year

Evaluation Type	Observed/Predicted Ratio	Observed – Predicted Difference (inches of precipitation or SWE)
Precipitation December-March Linear	0.97	-0.65
Precipitation December - March Multiple Linear	1.01	0.25
Snow April 1 Linear	1.17	4.83
Snow April 1 Multiple Linear	1.16	4.70
Mean of Results	**1.08**	**2.28**

7.0 SUMMARY, HISTORICAL UTAH PROGRAMS AND RECOMMENDATIONS

7.1 Summary

Salt Lake City sponsored earlier winter cloud seeding programs targeting the Six Creek's drainage basin in Water Years 1989 through 1996, with NAWC operating these programs. NAWC analysis of potential effects of the seeding indicated positive effects (~6% to 17% for water years 1989 and 1990, Thompson, et al, 1990). It was NAWC understanding that this program was discontinued following water year 1996 due to budgetary considerations.

SLCDPU expressed an interest in the fall of 2018 in re-establishing a cloud seeding program to impact the Six Creek's drainage basins that provide runoff to the Salt Lake Valley. This interest was expressed in a letter to Candice Hasenyager, coordinator of the Utah Division of Water Resources cloud seeding programs, that would enable cost sharing of this program with the Utah Division of Water Resources (e.g., up to 50% cost sharing state support).

NAWC contacted the SLCDPU and it was agreed that NAWC would prepare a proposal to conduct a program for the 2018-2019 winter season (NAWC proposal (# 18-429)). The goal of the program would be to augment the flows of City Creek, Emigration Creek, Parleys Creek, Mill Creek, Big Cottonwood Creek and Little Cottonwood Creek. Figure 1.1 provides a map of the proposed target area (e.g., six creeks drainage areas above 6000 feet MSL). The SLCDPU accepted this proposal and an agreement was signed effective November 19, 2018.

This season's cloud seeding program for Six Creeks program began on December 21, 2018 and ended on April 18, 2019. A total of 20 storm events were seeded during all or portions of 32 days using a network of nine ground-based silver iodide generators. Three of these events occurred in December, three in January, four in February, six in March and two additional seeding events in April. A 1270.75 cumulative hours of seeding generator operations were conducted during the season from the ground sites. Seeding suspensions were enacted during the second week of April for the target area as snow water equivalent (SWE) values exceeded suspension thresholds. Figure 7.1 shows the April 1st USDA snowpack basin percentage of median map.

Snowpack/precipitation was well above normal in the Six Creeks project area during the 2018-2019 winter season. As of April 8, 2019, sites in the Six Creeks target area reported snowpack water content ranging from about 138% to 227% of the <u>median,</u> with an overall basin value of 170% of the <u>median</u> snowpack.

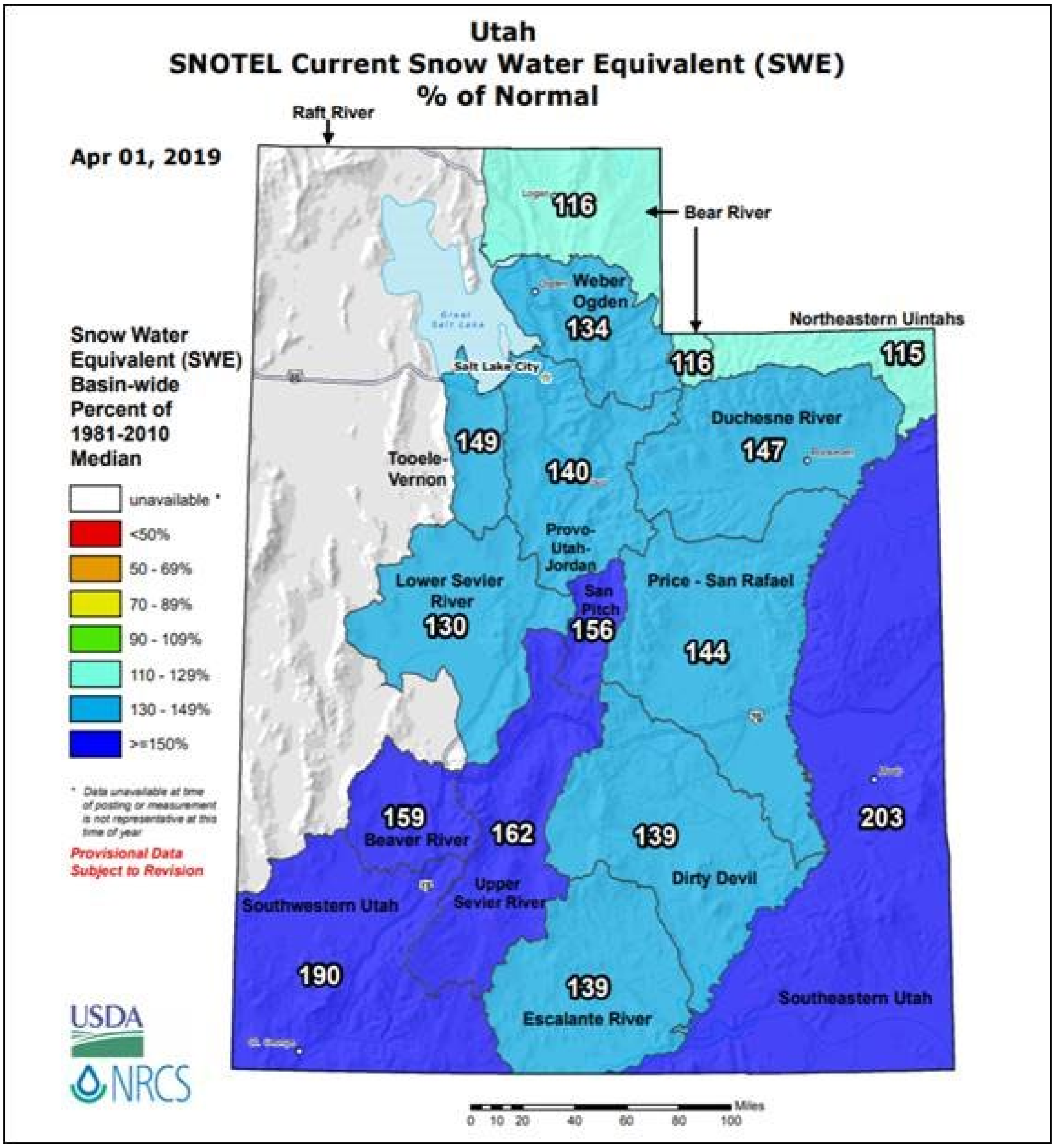

Figure 7.1 Utah Percent of Median April 1, 2019 Snow Water Content

Target/control evaluations were developed for the Six Creeks seeding program, utilizing NRCS SNOpack TELemetry (SNOTEL) precipitation and snow water content data. The precipitation evaluations include those utilizing both December – March and November – April totals. However, only the December – March regressions were applied to the current season since seeding operations began in mid December. The other evaluations were based on April 1 snow water content (SWE) values. The same set of target and control sites was utilized for the various evaluations, which includes five target and three control sites as detailed in Section 6.3 of the report. For each data type (i.e. December – March precipitation, November – April precipitation, and April 1 SWE), both linear and multiple linear regression equations were developed.

Results of the regression analyses for the 2019 water year were mixed, with the precipitation evaluations (December – March, linear and multiple linear) yielding observed/predicted ratios of 0.97 and 1.01, respectively. Ratios above 1.0 would be suggestive of an increase in target area precipitation due to seeding, while values near or below 1.0 are not. Given that these two values are close to 1.0, they are not suggestive of a seeding effect. In contrast, the snowpack evaluations (April 1 SWE, linear and multiple linear) single-season yielded ratios of 1.17 and 1.16, respectively. These are suggestive of increases to the natural snowpack (16-17%) that could be attributed to seeding operations. An average of the four target/control results summarized here yields a ratio of 1.08, which could be suggestive of an **8% overall increase in precipitation/snowpack due to seeding**. This would be the equivalent of over 2" of additional water in the target area during the season. However, it needs to be emphasized that single-season results are not considered statistically significant for this type of target/control evaluation. In general, the evaluation of at least 10-15 seeded seasons is considered necessary to get a reasonably good estimate of the seeding effects using such evaluation techniques for this type of program.

7.2 Historical Utah Winter Cloud Seeding Programs

Most mountain ranges in Utah have been the targets of winter cloud seeding programs since 1988 with one program dating back to 1974. Figure 7.2 provides the locations of these target areas. A NAWC peer reviewed paper was published in the Weather Modification's *Journal of Weather Modification* in 2009 (Griffith, et al, 2009) that provided summary information on the four long-term Utah winter cloud seeding programs. Target/control evaluations, similar to those discussed for the

Six Creek's program, provided estimated increases in precipitation or snow water content ranging from +3% to +21%.

The value of the Utah winter cloud seeding programs was also demonstrated in an independent study performed by the Utah Division of Water Resources entitled "Utah Cloud Seeding Programs, Increased Runoff/Cost Analyses" (Stauffer and Williams, 2000). This report used estimates of increases in April 1st water content from an earlier NAWC annual project report (similar to this one), but with verification of those numbers by the Utah Division of Water Resources, to estimate increases in streamflow due to cloud seeding. This report was updated in 2012 (Hasenyager, *et* al, 2012) and results for the various seeding target areas in Utah are summarized in Table 7-1.

Table 7-1
Increased Runoff and Cost for the Utah Cloud Seeding Programs

Project	Increased Runoff (ac-ft)	Cost ($)	Cost ($/ac-ft)
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

This report estimated an average total 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.**

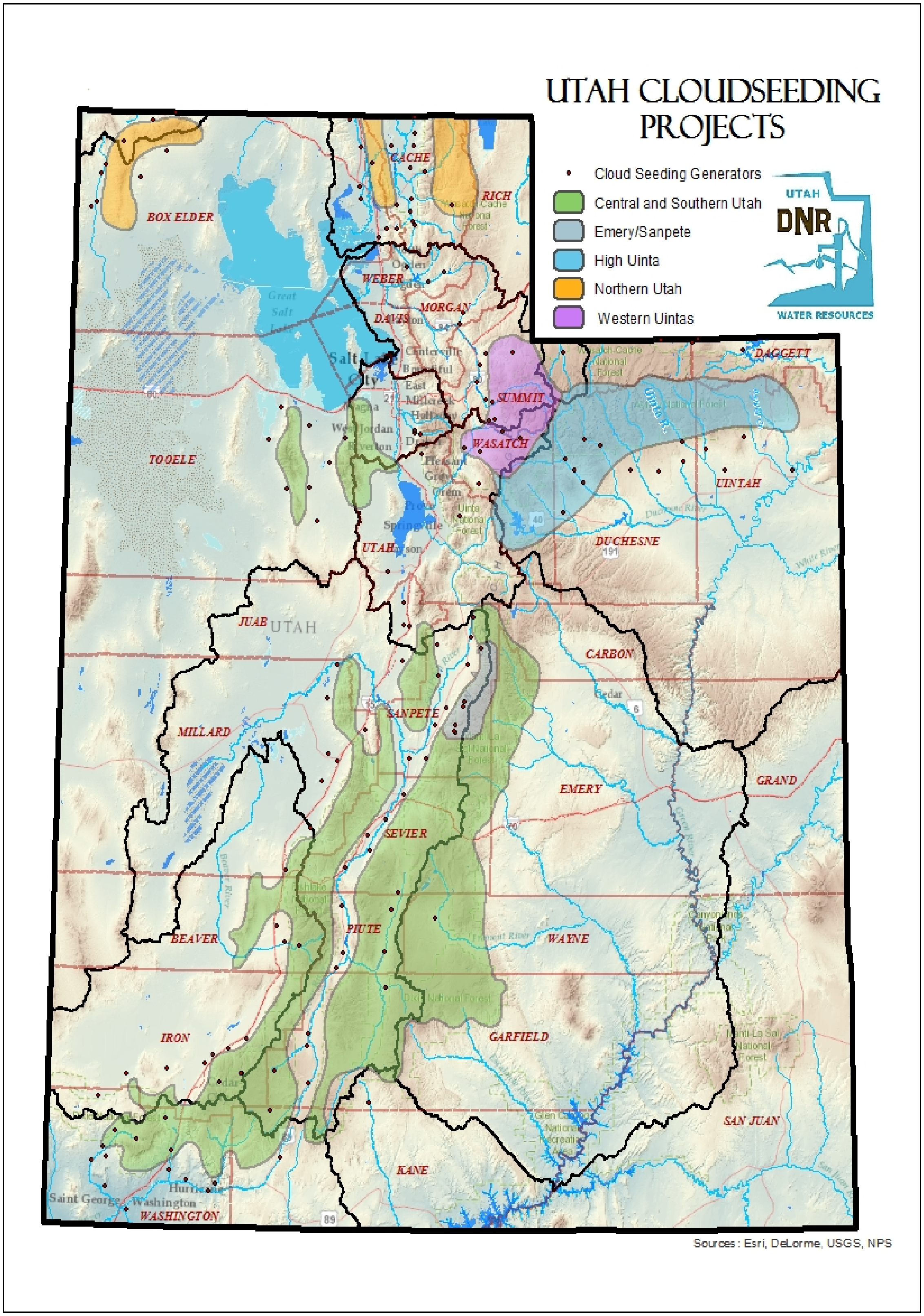

Figure 7.2 Utah Winter Cloud Seeding Target Areas

An independent analysis of the Central/Southern Utah program **primary target area** seeding effectiveness was conducted by a statistical consulting firm (Mason and Chaara, 2007). Their summary statement regarding that evaluation follows: "This difference falls in a range of 0.218 to 2.437 inches of increase in average December through March precipitation in the target area. The analysis led to a p-value of 0.0465 for the Mann-Whitney test for difference; this is significant at the 5% level. It is noted that these data were from a non-randomized data set." The stated difference would be in the range of 2-20%. Importantly, the 5% significance level indicates a 95% statistical confidence that the indicated increase is not due to chance. The consultant further states that their analysis "supports the claim that the seeding program leads to a 10% or more increase in precipitation".

It is concluded, based on NAWC's evaluations, the UDWR independent analysis, and the evaluation conducted by the statistical consultant, that winter season cloud seeding in Utah is a viable, cost-effective method for enhancing water supplies. The cost to produce the additional water is very low and the attendant program benefit/cost ratio very attractive.

7.3 Recommendations

It is recommended that the winter seeding program for the Six Creeks Target area be continued. Routine application of weather modification technology each year can help stabilize and bolster water supplies (both 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, are that 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 (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, and 4) seeding in normal and above-normal water years will provide additional water supplies (surface and underground carryover) for use in drier water years.

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

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APPENDIX A

MEDIA RELEASES

This appendix shares the media releases that were associated with the Six Creeks Project during the 2018-2019 season. As is typical with new projects in an area, the media is generally interested in sharing with the public how cloud seeding works and personnel associated with the project. Two news stories were developed during the 2018-2019 for the project, one by KSL News and the other by Fox News. The first story below is that by KSL and was also picked up by Desert News. The second, which isn't here, as it was only a video clip and no transcript was developed from the local Fox News affiliate. Both showed how cloud seeding operations would help to increase snowfall along the Wasatch Front.

Salt Lake's cloud-seeding efforts 'give Mother Nature a little something extra to work with' during snowfall

By John Hollenhorst

Published: February 11, 2019 8:03 am

Ken Fall, Deseret News

Meteorologist Stephanie Beall fires up a cloud-seeding device near the mouth of Big Cottonwood Canyon on Saturday, Jan. 5, 2019. She explains the machine is supposed to squeeze more snow out of passing storms.

SALT LAKE CITY — For the first time since the 1990s, Salt Lake City is trying to make more snow than what nature has in mind.

The city has joined a long-running cloud-seeding effort aimed at squeezing more snow out of passing storms.

As meteorologist Stephanie Beall fired up a cloud-seeding device near the mouth of Big Cottonwood Canyon, she said it's to "give Mother Nature a little something extra to work with in order to create more snowfall."

Ken Fall, Deseret News

Meteorologist Stephanie Beall fires up a cloud-seeding device near the mouth of Big Cottonwood Canyon on Saturday, Jan. 5, 2019. She explains when conditions are right, the burner goes for hours, day and night, pumping silver iodide into the storm. She said it gives Mother Nature a little something extra to work with in order to create more snowfall.

Snow that falls in the Wasatch Mountains will be drinking water someday, and that's why it benefits the city if cloud seeding makes more snow in the drainage above the Big Cottonwood Canyon water treatment plant.

Beall works for a company called North American Weather Consultants. She uses gear that looks a lot like the chimney starter on a charcoal grill. The "little something extra" is propane to make heat, which vaporizes a chemical mixture.

The heat launches a blast of silver iodide particles into the sky.

Just as she was getting started, Beall started to smile because the wind picked up and stiffened a flag that was fluttering on a nearby flagpole.

"It's telling me that there's colder air moving in," Beall said, "and the seeding conditions are going to get better."

As the snowstorm developed and moved east into the mountains, she seemed positively excited by the white stuff falling around her.

"The big flat flakes are the one's we kind of like to see," she laughed, "so, sorry. I'm a weather nerd. I can't help it."

Ken Fall, Deseret News

Snow is falling near the mouth of Big Cottonwood Canyon on Saturday, Jan. 5, 2019. Salt Lake City is trying to make more snow with the help of a cloud-seeding device.

When conditions are right, the burner goes for hours, day and night, pumping the silver iodide into the storm. Somewhere to the east the tiny particles become billions of little gathering points for moisture.

"They start to form ice crystals," Beall said. "They form snowflakes. They get heavy. They fall. And then you have snow."

If things go well, it creates more snow than might have fallen otherwise, according to Don Griffith, president of North American Weather Consultants. His company has a new contract this year with Salt Lake City.

"We call it the Six Creeks Program," he said, "because what we're trying to do is increase the snowpack in the six drainages that surround the Salt Lake Valley to the east."

Snowbird and Alta ski resorts have paid for the cloud-seeding service for many years. But this is the first time in a quarter-century that Salt Lake City officials have figured it's worth the money.

"You know, we're the water provider for 350,000 people," said Jesse Stewart, deputy director of Salt Lake City Public Utilities. "We're looking at making sure we have a reliable source going forward."

The city isn't facing an immediate crisis, but a long-term drought has plagued much of Utah for the last two decades. City officials want to diversify their water sources to weather any future crises.

"Would we be fine without the cloud seeding? Probably," Stewart said. "But we want to look at what can we do, just to give ourselves that buffer."

State officials say studies show that cloud seeding really does boost the output of storms.

"The increase in precipitation is between a 5 and 15 percent increase," said Candice Hasenyager, of the Utah Division of Water Resources.

In the view of state water planners, the effort is worth real money. Cloud seeding is far cheaper than building new dams and reservoirs because it produces water at $3 or less per acre-foot.

"If we went out and developed a brand-new project," Hasenyager said, "you're looking at a thousand dollars an acre-foot."

The state this year is providing $300,000 in matching funds for local governments and water districts to pay for the cloud seeding. The practice has been going on in various parts of the state since a major drought in the early 1970s.

Over the years, some critics have questioned whether it's a good idea to interfere with nature.

"Unnatural versus natural? I would say for the most part we're just helping Mother Nature a little bit," Beall said, "in a good way."

APPENDIX B

COMPUTER MODELING

NAWC utilizes various computer models in the conduct of cloud seeding programs. These models are of two basic types. First, there are a variety of models that forecast a variety of weather parameters useful in the conduct of the cloud seeding program. These include global models such as the Global Forecast System (GFS), European Center (EC) Model, and regional models such as the North American Model (NAM), Weather Research and Forecasting (WRF), and High-Resolution Rapid Refresh (HRRR) which is part of the WRF Model. Secondly, there are models that predict the transport and diffusion of seeding materials (e.g., HYSPLIT). Some model data was archived on NAWC computers while significant amounts of other data are archived and available on the internet.

For a good portion of the history of many seeding programs, NAWC has used the standard National Oceanic and Atmospheric Administration NOAA) atmospheric models such as the NAM and GFS in forecasting seedable events and associated parameters of interest (e.g. temperatures, winds, precipitation). NAWC has continued to use these models, especially for longer range forecasts. A more sophisticated model has been utilized more recently for shorter range forecasts. This is the Weather Research and Forecasting (WRF) model developed by the National Center for Atmospheric Research (NCAR) and NOAA. This model has shown considerable skill in predicting precipitation, pressure fields, wind fields, convective activity and a variety of other parameters of interest in conducting the cloud seeding operations.

During the 2017-2018 season, NAWC began utilizing in-house software developed by personnel at Idaho Power Company to display data from the High Resolution Rapid Refresh (HRRR) model. The program or script was developed by personnel at Idaho Power to ingest hourly 3-km HRRR model data and produce specialized plots of parameters of interest to those in the weather modification field. The model displays graphical output of where liquid water and dewpoint depressions are occurring from a user-specified location. This model was one of those utilized in the operation of the Six Creek program during the 2018-2019 season.

The HYSPLIT model, developed by NOAA, provides forecasts of the transport and diffusion of either ground-based or aerial releases of a given material, which in this case would be silver iodide seeding particles. NAWC has utilized this model in some cases to help with analysis of the targeting of seeding material from specific sites. The WRF, in house-HRRR and HYSPILT models will be discussed separately in the following.

GFS, EC and NAM Models

These global/regional forecast models are probably the most widely accessed online for a wide variety of applications, with a variety of sources that display various types of forecast data from these models. This help with identification of upcoming events that may be suitable for cloud seeding, as well as guidance during a seeding event. They are generally available at a 6-hour time resolution out to several days (NAM) and 10 days or more (GFS, EC). NAWC frequently uses temperature, wind, humidity, and precipitation forecasts from these models guidance during operational periods.

WRF Model

The Weather Research and Forecasting (WRF) Model is a newer mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. It features multiple dynamical cores, a 3-dimensional variational (3DVAR) data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers.

The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. WRF provides operational forecasting a model that is flexible and efficient computationally, while offering the advances in physics, mathematics, and data assimilation contributed by the research community.

NAWC often utilizes NOAA's Earth Systems Research Laboratory's HRRR version of the WRF model for operations. This model has a 3km grid spacing compared to the more standard grid model spacing of 12km (e.g. NAM model), and it is re-initialized every hour using the latest radar observations (in comparison to the NAM, GFS, and EC models which are currently re-initialized every 6 hours). Hourly forecast outputs from the HRRR model are available for a variety of parameters out to 15 hours. Table 1 provides a summary of some of forecast parameters of interest in conducting the cloud seeding program.

Table 1 HRRR Forecast Parameters of Interest

Parameter	Application
1km above ground level reflectivity	Forecast of areas of significant precipitation during storm periods based on precipitation a 1km above the surface
Composite reflectivity	Forecast of areas of significant precipitation at any level of the atmosphere
Maximum 1 km above ground level reflectivity	Forecast of areas of heavier precipitation, especially in convective cases
1 hour accumulated precipitation	Forecasts of radar derived estimates of precipitation reaching the ground in a one-hour period (QPF).
Total accumulated precipitation	Forecasts of radar derived estimates of precipitation reaching the ground for a specified time period, for example 1-6 hours in the future (QPF).
Winds	Forecasts of the winds at 850-mb (5,000 feet) and 700-mb (~10,000 feet) are useful in determining which seeding sites to use, and the period of operations at each site.
700-mb temperature	NAWC typically uses this level, which is approximately 10,000 feet above sea level, to indicate whether silver iodide will activate.
700-mb vertical velocity	Forecasts the strength of the upward or downward movement at the 700-mb (i.e. 10,000 foot) level. Stronger updrafts favor transport of seeding material to colder cloud regions.
Echo top height	Forecasts of cloud echo tops. Can be useful in determining whether the cloud tops are forecast to be cold enough for silver iodide to be effective or too cold.

Figure 1 is an example of a forecast at a 10-hour lead time from the HRRR model of composite radar reflectivity over the southwestern U.S. valid on March 25, 2012. Figure 2 is a corresponding forecast of one-hour total precipitation accumulation. Comparison with observed surface precipitation have been conducted in many cases, verifying the general accuracy of the HRRR model precipitation fields in most situations. Comparison of other types of data in the model (such as supercooled liquid water, or SLW) has also been compared to various types of observations to assess the model's degree of accuracy in forecasting these parameters. While the results of these comparisons vary somewhat among different model parameters and differing geographical areas, this is an area of investigation that is useful for operations cloud seeding an in which NAWC has been involved.

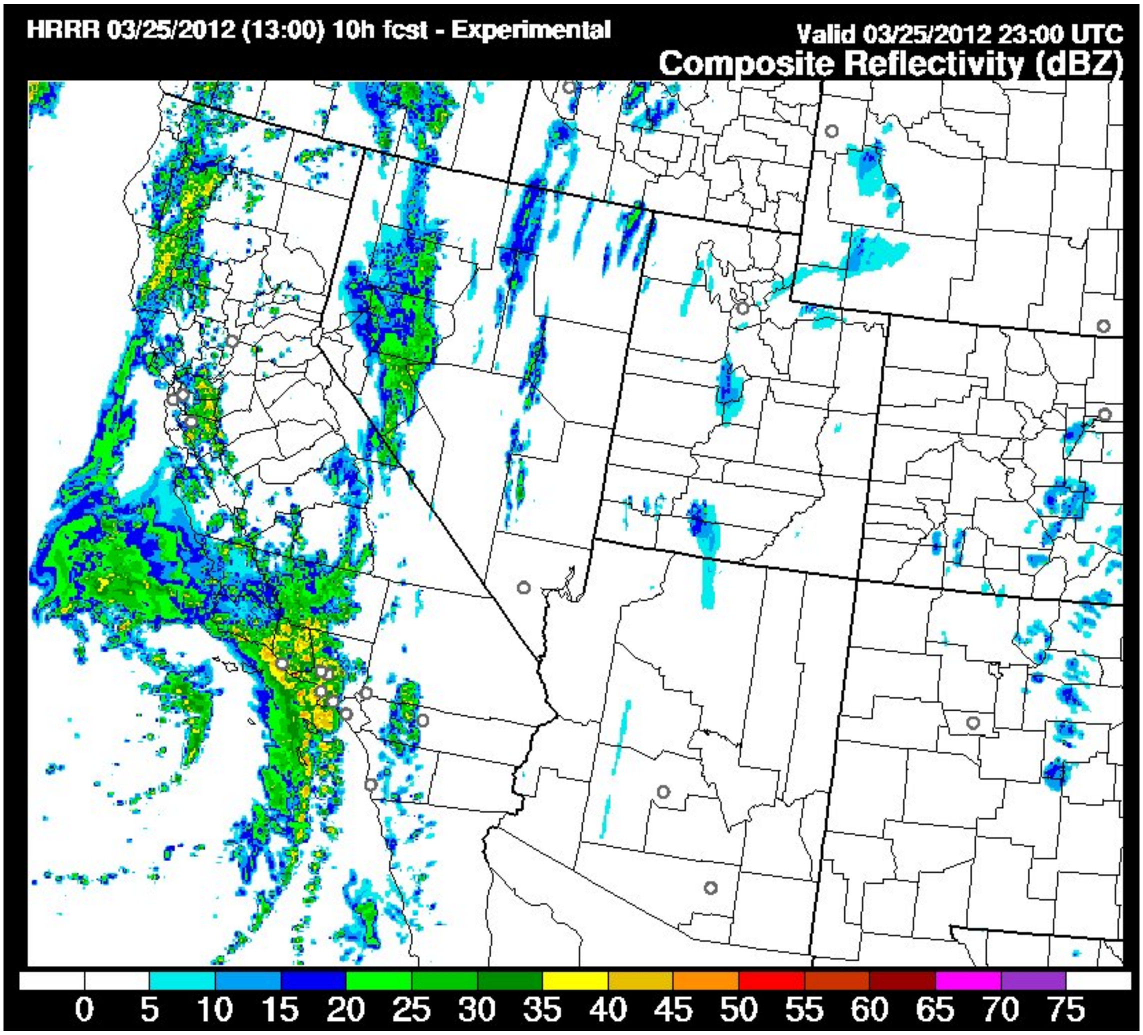

Figure 1 HRRR Model ten-hour forecast of composite radar reflectivity on March 25, 2012

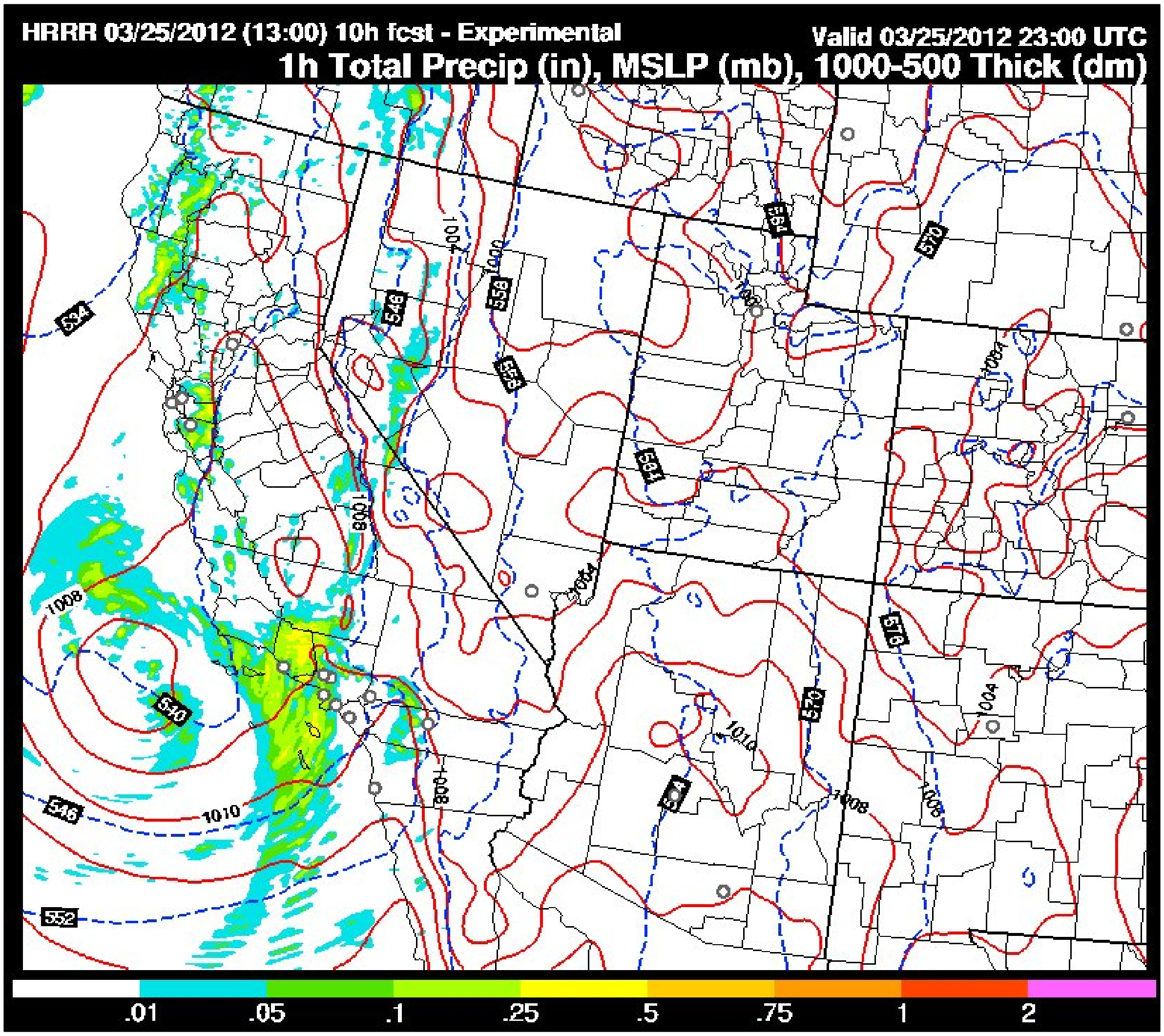

Figure 2 HRRR model ten-hour forecast of one-hour precipitation during an event on March 25, 2012

<u>In-House HRRR Model Customized Data Displays</u>

During the summer of 2017, NAWC collaborated with Idaho Power in order to utilize a script that has the ability to ingest and create customized displays of 3-km HRRR model data. This script allows the user to define a grid where seeding operations may be occurring. The user can also specify vertical cross and sounding profiles sections in these areas of interest. In these cross sections, liquid water is typically plotted as with temperatures, allowing the user to identify areas in the model data with significant SLW at or below -5 degrees C. This script was also utilized in a variety of different areas where the HRRR model data could be compared to aircraft icing reports, radiometer data and ridge-top icing meter data. Figure 3 shows some example of the products generated by the script. The upper left panel displays vertically-integrated liquid (VIL), a measure of the total cloud liquid water forecast above each point. The red line with endpoints defines the vertical cross section display in the upper right panel. The lower left panel is dewpoint depression (an approximation of humidity) for the same cross section, while the lower right panel shows the percentage of cloud liquid water as compared to ice for this same vertical profile. These products can all be useful to the project meteorologist.

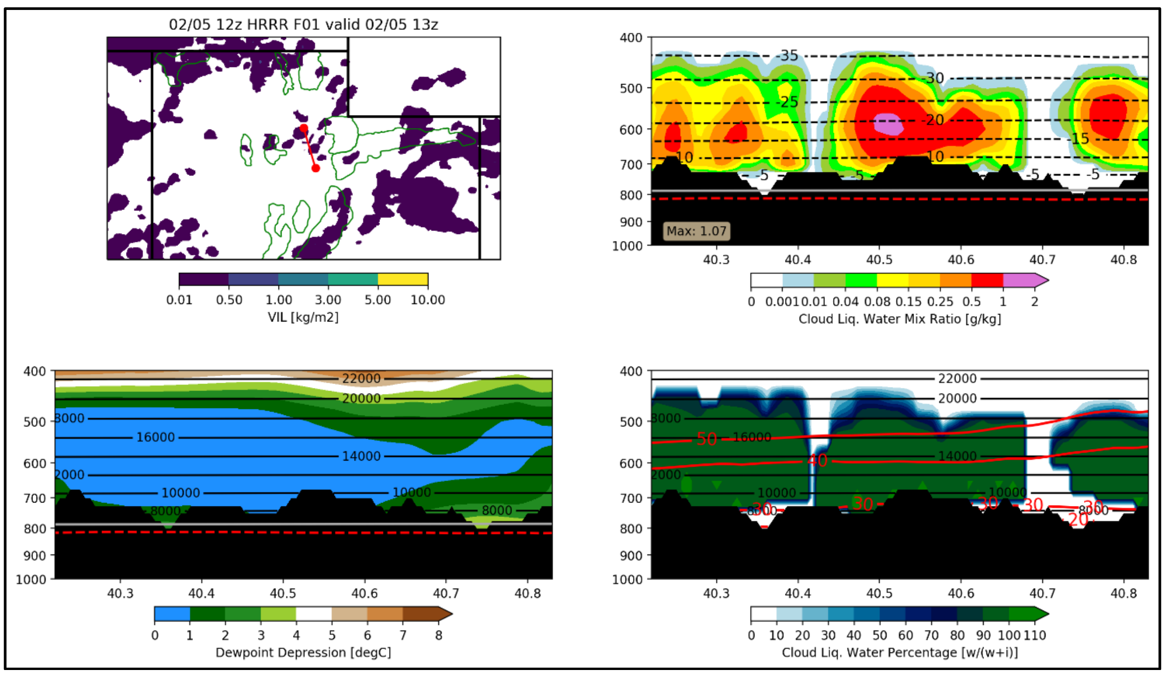

Figure 3 HRRR Forecast of Super Cooled Liquid Water

HYSPLIT Model

The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model is the newest version of a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations. The dispersion of particles released into the atmosphere is calculated by assuming either puff or particle dispersion. In the "puff" mode, puffs expand until they exceed the size of the meteorological grid cell (either horizontally or vertically) and then split into several new puffs, each with its share of the material mass. In the HYSPLIT particle mode, a fixed number of initial particles are advected about the model domain by the mean wind field and a turbulence component. The model's default configuration assumes a puff distribution in the horizontal and particle dispersion in the vertical direction. In this way, the greater accuracy of the vertical dispersion parameterization of the particle model is combined with the advantage of having an ever-expanding number of particles represent the material distribution.

The model can be run interactively online through the READY system on the NOAA site, or the code executable and meteorological data can be downloaded to a Windows PC. The online version has been configured with some limitations to avoid computational saturation of the web server. The registered PC version is complete with no computational restrictions, except that the user must download the necessary meteorological data files. The unregistered version is similar to the registered version except that it will not work with forecast meteorology data files.

Figure 4 provides as example of HYSPLIT output which shows the individual plume forecasts for each potential seeding site. This forecast is independent of the type of material released, but assumes that the material is conserved in the atmosphere and does not include secondary processes such as precipitation or nucleation of the material.

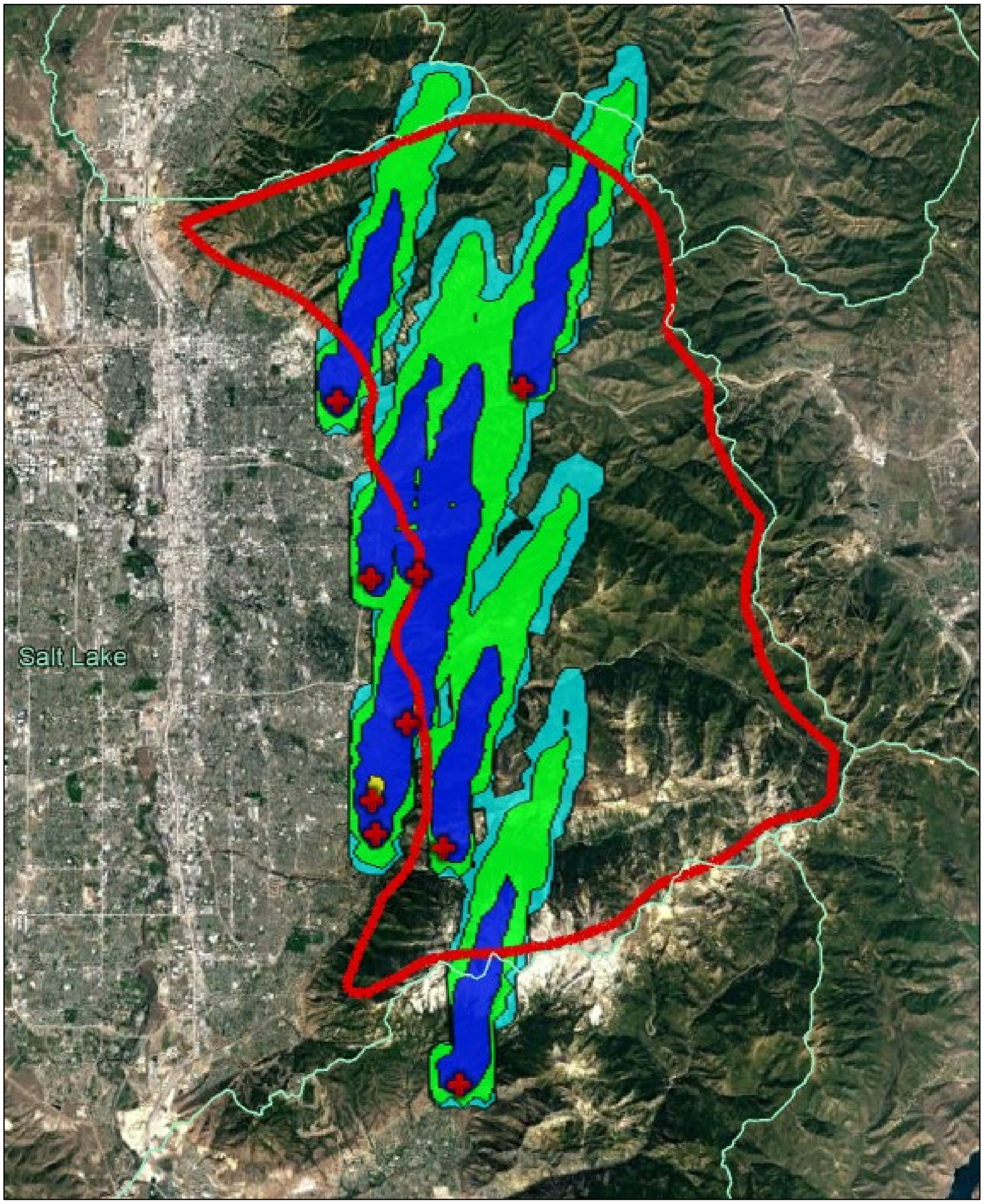

Figure 4 HYSPLIT Model Output Example from the 2018-2019 Winter Season

The seeding material (e.g. silver iodide) needs to interact with the atmospheric SLW to form ice crystals. These can subsequently grow into snowflakes and precipitation over the target area, essentially enhancing the natural process of snow development. These processes obviously occur downwind of the seeding sites. This type of display can be useful in the selection of which seeding sites are favorable in a given situation.

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