Cloud Seeding Annual Report and Evaluation

Six Creeks Program

2023-2024 Winter Season

Prepared For:

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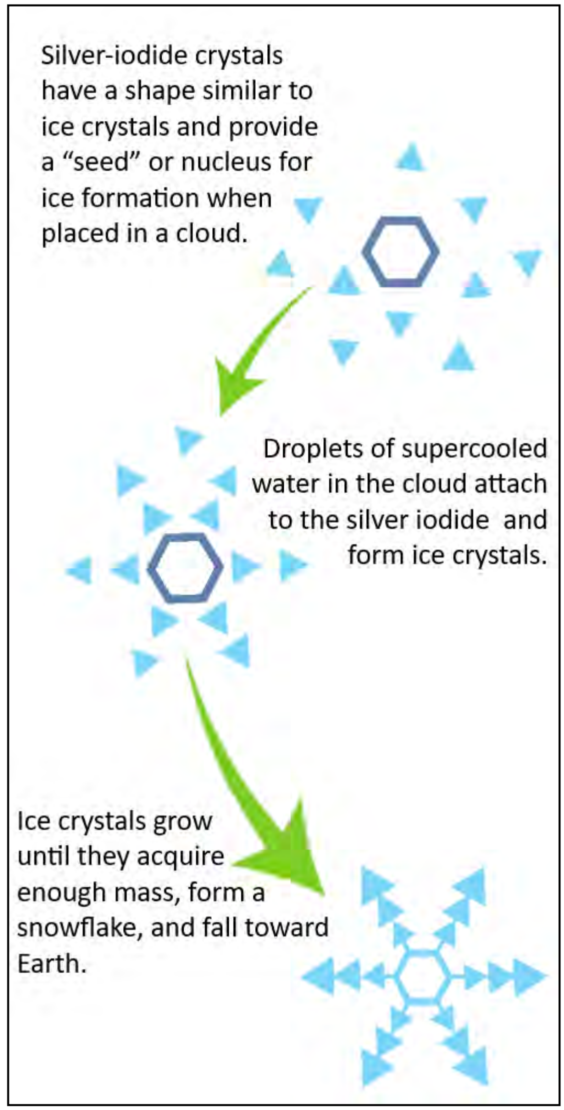
CLOUD SEEDING OVERVIEW

The Science

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

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

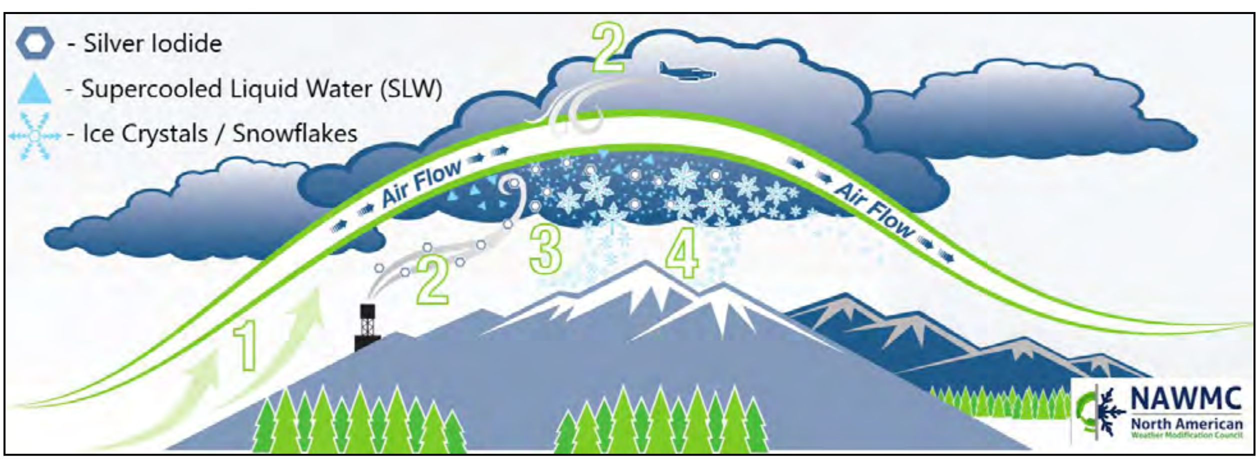


Safety

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

Effectiveness

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



CLIMATE TRENDS

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

The current 30-year average is based on the period of 1990 – 2020. Images in Figure 1 and 2 show how each 30-year average for the past 120 years compares to the composite 20th century average for temperature and precipitation. For the western U.S., the 1990-2020 average show much warmer than average temperatures, in comparison to the 100-year 20th century average. When comparing precipitation for the past 30 years to both the previous 30-year average and the 1901-2000 average, the American Southwest (including portions of Utah, Arizona, California and Nevada) has seen as much as a 10% decrease in average annual precipitation.

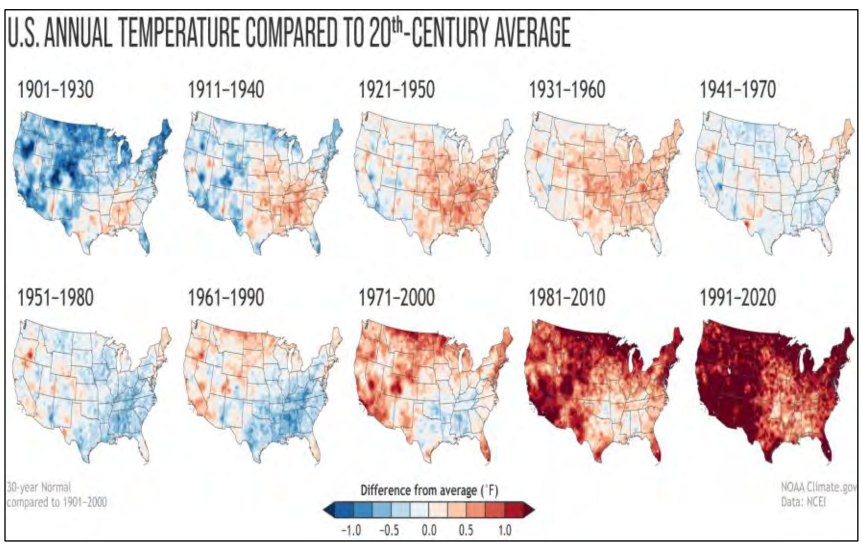


Figure 1 **U.S. Annual Temperature compared to 20th-Century Average**

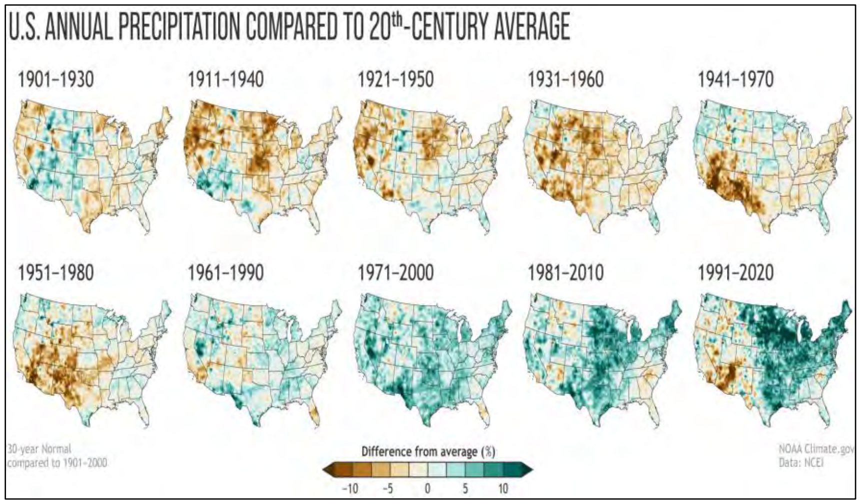


Figure 2 **U.S. Annual Precipitation compared to 20th-Century Average**

The 2023-2024 water year was again above average in terms of precipitation and snowpack, although to a lesser degree than the previous season which was extremely wet. The south arm of the Great Salt Lake (as of mid-May 2024) is at roughly 4,195 feet. Figure 3 is a long term graph of lake levels for both the north and south arms of the lake. The current levels have improved to roughly pre-2021 values but are still below optimal for many ecosystems and industries (Figure 4).

Figure 3 Great Salt Lake levels since 2007 (graph from the greatsaltlake.utah.gov website)

EXECUTIVE SUMMARY

Program History

Salt Lake City Department of Public Works (SLCDPW) initially sponsored winter cloud seeding programs targeting the Six Creeks 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's understanding that this program was discontinued following water year (1996) due to budgetary considerations.

SLCDPW expressed an interest in the fall of 2018 in re-establishing a cloud seeding program to impact the Six Creeks drainage basins that provide runoff to the Salt Lake Valley. A proposal was drawn up by NAWC and accepted by SLCDPU in the fall of 2018, and the first season of operations for the current program began in December 2019.

The current season's cloud seeding program began on November 15, 2023 and was contracted through April 15, 2024. A total of 37 storm periods were seeded during the 2023-2024 season, using a network of eight ground-based silver iodide generators. In total there were two seeded events for the Six Creeks program in November, four in December, ten in January, ten in February, nine in March (including one split between March and April), and an additional two seeded storms in April. A total of 1,321.75 cumulative hours of seeding generator operations were conducted specifically for the Six Creeks program during the season (which excludes seeding for the Snowbird program within the Six Creeks watershed).

Snowpack and precipitation this season began on the low side, but improved to above average during the first few months of 2024. There was an El Niño pattern in place this season, in contrast to the past few seasons. As of April 15, 2024, sites in the Six Creeks target area reported snowpack water equivalent (SWE) values ranging from roughly 110% - 150% of the average (median) across most of the watershed, resulting in a basin snowpack average of roughly 130% of the mid-April median.

Results

To evaluate the increase in snowpack and precipitation resulting from cloud seeding, long term Target/control evaluations have been performed during both seeded and non-seeded years for the Six Creeks seeding program. Results of these evaluations indicate a roughly 6% increase in precipitation and/or snowpack resulting from cloud seeding. This additional 6% increase in snowpack is equivalent to about 1-2 inches of SWE in the target area, depending on overall seasonal trends.

The relationship between snowpack and realized streamflow is generally not linear (improved efficiency at higher runoff rates). Additional evaluations were, therefore, conducted to determine the projected increase in runoff resulting from a 6% increase in snowpack. These mathematical evaluations yielded an expected 8-12% increase in streamflow for Little Cottonwood Creek and Red Butte Creek (depending on overall seasonal performance).

These results are discussed in more detail in Section 6.4 of the report.

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, as occurred in early 2023, should snowpack accumulate to the point where additional water may not be beneficial.

1. INTRODUCTION

The history of cloud seeding operations for the Six Creeks drainage basins dates back to the late 1980s. Salt Lake City has sponsored winter cloud seeding programs targeting the area 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 (about 6% to 17% for water years 1989 and 1990, Thompson et al., 1990). It was NAWC's 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. NAWC contacted the SLCDPU to conduct a program beginning in the 2018-2019 winter season (per an agreement effecting on November 19, 2018). 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 is a map of the proposed target area (e.g., six creeks drainage areas above 6000 feet MSL). The program has generally been conducted between about mid-November and mid-April in the subsequent seasons. This report focuses on the design, implementation, and operation of the program for the 2023-2024 season.

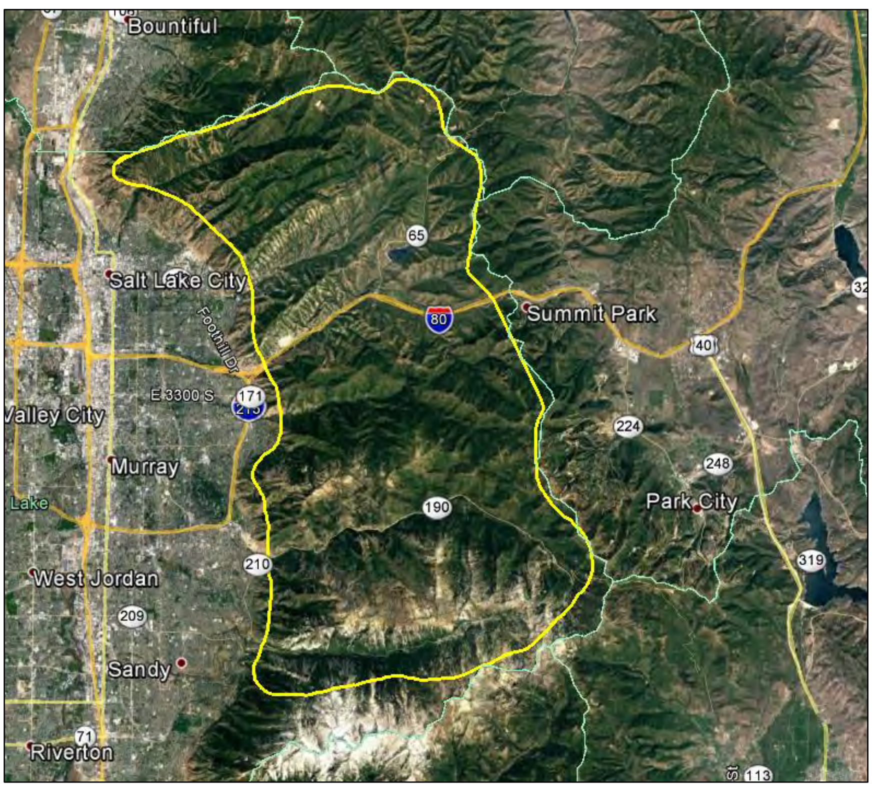


Figure 1.1 **Six Creeks Target Area**

2. CLOUD SEEDING THEORY

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, 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, it is possible for cloud water droplets to remain in a liquid state while below the freezing point (supercooled), as a function of the purity of the cloud water droplets. In a laboratory environment, pure water droplets can remain unfrozen down to a temperature of -39°C. These supercooled cloud droplets are what causes icing to occur on aircraft. Some types of particles in the atmosphere (referred to as ice nuclei or freezing nuclei) include things such as dust or salt particles, or even bacteria. A supercooled cloud droplet can freeze 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 or 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 can grow due to surrounding water vapor, 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, or as rain if surface temperatures are warmer than freezing.

Research conducted beginning in the late 1940’s demonstrated that tiny particles of silver iodide could mimic natural particles and serve as freezing nuclei at temperatures colder than -5°C. In fact, these silver iodide particles were shown to be much more active at temperatures between -5°C and -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. 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 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. This enhancement of the natural process can produce cold-season snow/precipitation increases in the targeted watersheds.

3. PROJECT DESIGN

Operational procedures during this season's 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 winter 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 such programs. NAWC has incorporated observational, seeding method and evaluation enhancements into the project when they are believed to be of practical value.

3.1. Seeding 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 and deal with meteorological characteristics (temperature, stability, wind flow and moisture content) associated with winter season cloud systems. The following points provide the seeding criteria, which NAWC has established for other Utah winter cloud seeding program:

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

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. After combustion, the silver iodide solution 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 cloud seeding nuclei generators were operated only during those periods when the temperatures within the cloud mass were between about -5°C and -25°C (+23°F to -13°F). Seeding will generally be effective within this range, if the cloud base is at a lower elevation than the mountain crest and no temperature inversions or other stable layers exist between the elevation of the cloud seeding generator and the cloud base. The existence of low-level inversions, or any significant stable layers, 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. For the seeding to be effective, the AgI crystals must become active in the cloud region which contains supercooled liquid water droplets, with sufficient downwind distance for the growth and precipitation process to affect the targeted areas. 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. As a clarification of this, winds in meteorology are reported as the direction from which the winds are blowing. For example, a southwest wind means the winds are blowing from the southwest towards the northeast.

3.2. Equipment and Design

The locations of the eight seeding generators are shown in Figure 3.1, with site information in Table 3-1. The sites were located to maximize their potential use during typical storm periods. The cloud seeding equipment at each site includes a cloud seeding nuclei generator and a propane gas supply tank. Figure 3.2 is a photo of the White Reservoir site. The seeding solution consists of 2% (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.

When a site is in operation, the propane gas pressurizes 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 roughly eight grams per hour.

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.

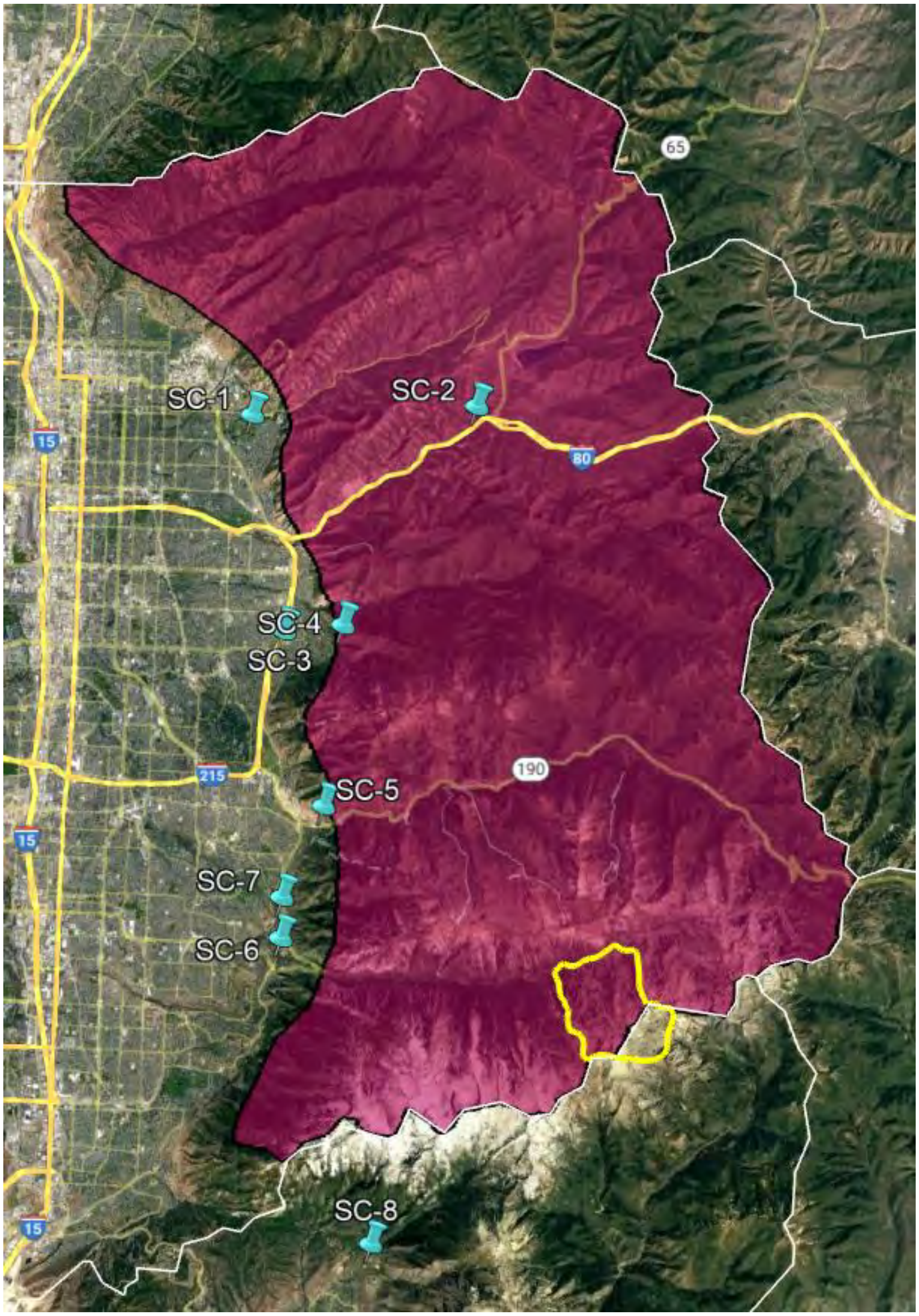


Figure 3.1 **Target Area (pink shading) and seeding sites (blue pins)**

Table 3-1
Seeding Site Locations

Site Number	Name	Latitude (°N)	Longitude (°W)	Elevation (feet)
1	Baskin Reservoir	40.744	-111.818	4835
2	Mountain Dell Treatment	40.749	-111.723	5380
3	45th South Pump Station	40.675	-111.801	4950
4	White Reservoir	40.677	-111.776	5620
5	Big Cottonwood Canyon Water Treatment	40.619	-111.782	4993
6	Little Cottonwood	40.576	-111.798	5170
7	Sandy Metro Water Plant	40.589	-111.799	5000
8	Alpine	40.479	111.755	5440

Figure 3.2 **White Reservoir cloud seeding site**

4. 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/highway cameras. This information helps NAWC meteorologists to determine when conditions are appropriate for cloud seeding. Each of NAWC's meteorologists also has access to these same products at home, to allow continued monitoring and conduct of seeding operations outside of regular business hours. Figures 4.1 – 4.5 show examples of some of the available weather information that is used in this decision-making process for operational cloud seeding programs.

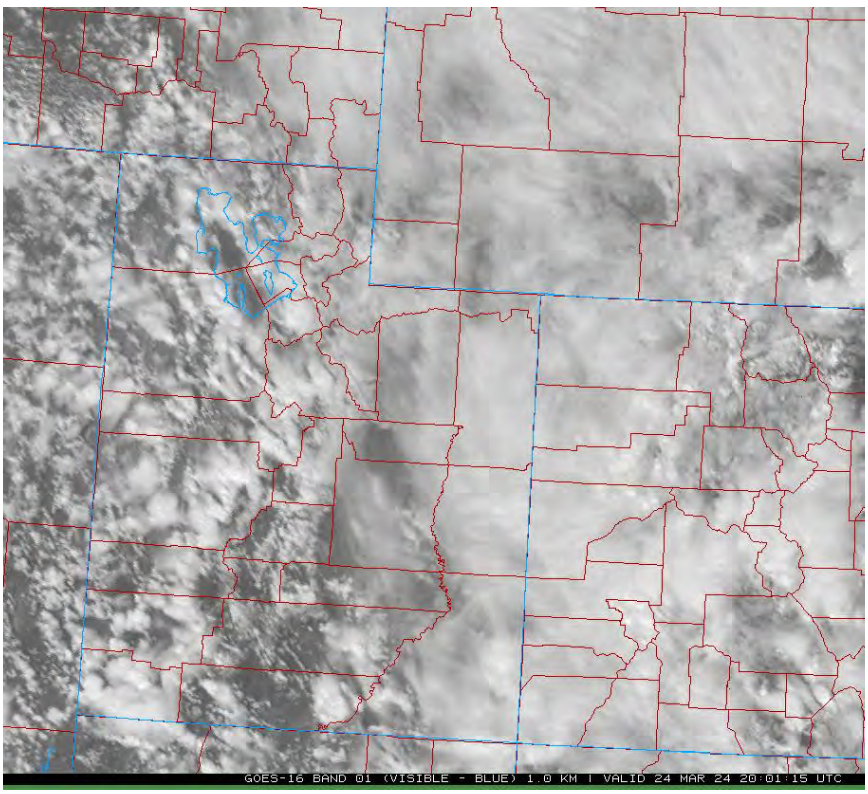


Figure 4.1 **Visible spectrum satellite image over Utah on March 24, 2024 during a seeded storm; bright white areas show heavier cloud cover associated with areas of precipitation and likely cloud liquid water**

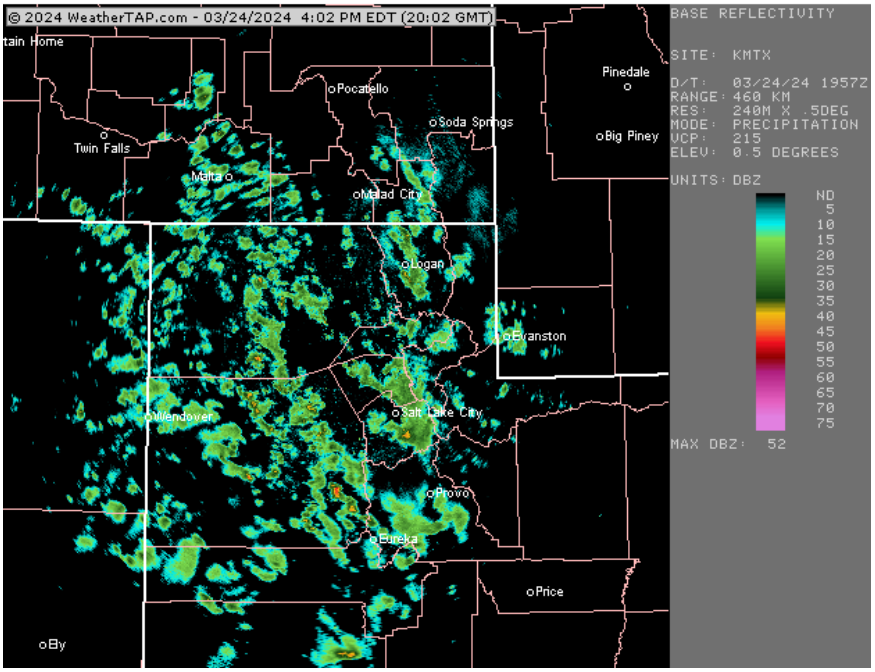


Figure 4.2 **Weather radar image on March 24, corresponding to the image in Figure 4.1, showing coverage and intensity of precipitation**

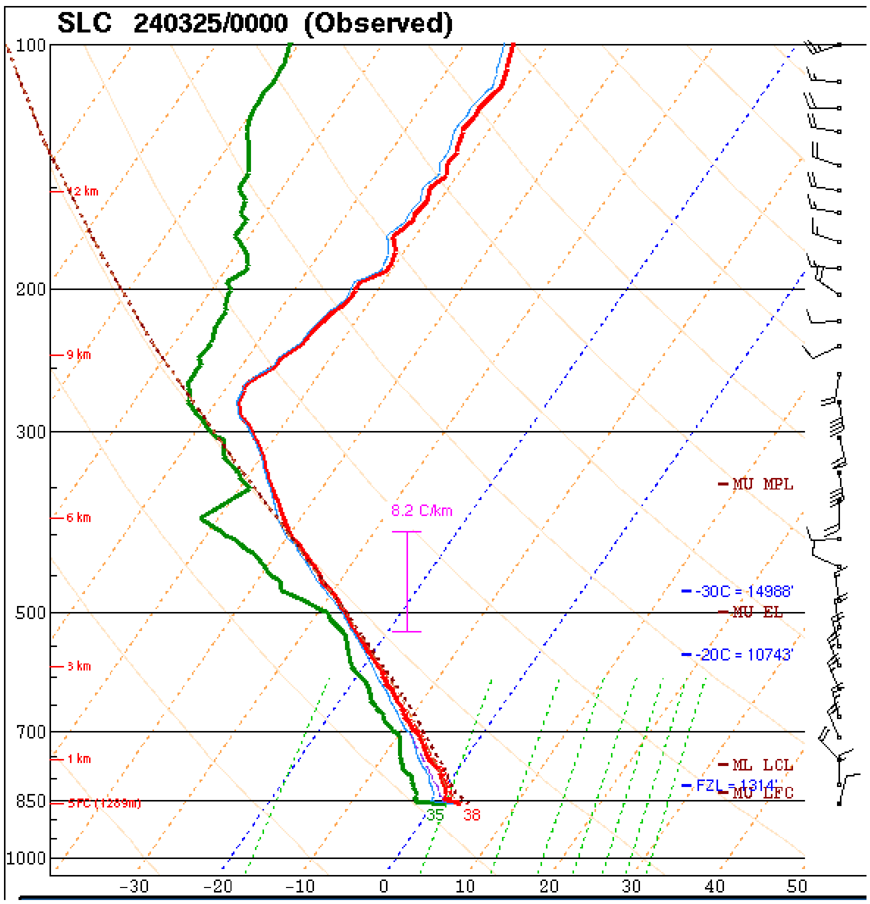


Figure 4.3 **Weather balloon sounding profile at Salt Lake City on the evening of March 24, 2024. These vertical atmospheric profiles include temperatures, moisture, and winds which are all important to seeding operations.**

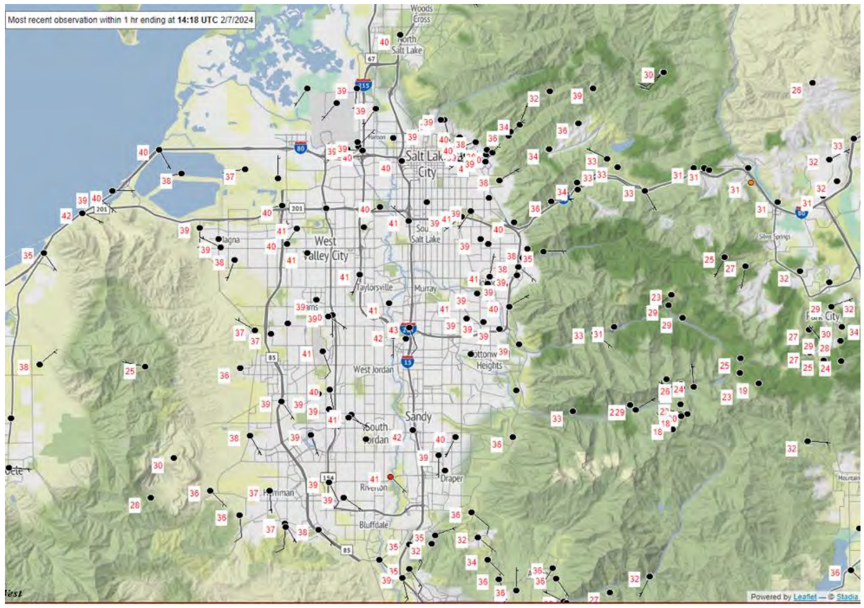


Figure 4.4 Map of surface observations (winds/temperatures) in the Salt Lake City area on February 7, 2024. Surface data are important for targeting of seeding material at ground-based sites.

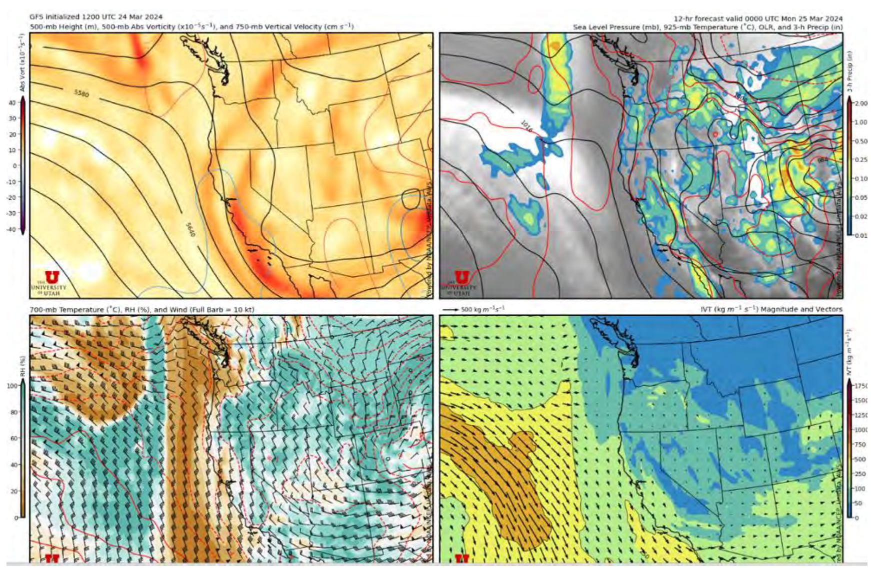


Figure 4.5 Example of GFS (Global Forecast System) model data during a March 2024 storm event. Forecast model data is widely used by program meteorologists in the analysis and forecast of conditions favorable to seeding operations.

5. OPERATIONS

5.1. Seeded Storm and Snowpack Data

This season's cloud seeding program for Six Creeks target area became active on November 15, 2023 and ended April 15, 2024. A total of 37 storm events seeded for the Six Creeks program, during all or portions of 47 calendar days. In total there were two seeded events in November, four in December, ten in January, ten in February, nine in March (including one split between March and April), and an additional two seeded storms in April. A total of 1,321.75 cumulative hours of seeding generator operations were conducted specifically for the Six Creeks program during the season.

Table 5-1 provides the dates and ground generator usage for the season. Tables 5-2 through 5-5 provide the hours of generator operations by generator site location. The tables and totals exclude seeding for the Snowbird program, within the Six Creeks watershed, conducted on some days during November and December.

Table 5-1
Storm Dates and Site Usage, 2023-2024 Winter Season

Storm Number	Storm Period	Number of CNGs Operated	Generator Hours
1	November 16	3	15
2	November 19-20	3	57.25
3	December 2-3	3	39
4	December 7	1	2
5	December 7-8	3	43.5
6	December 23	4	19.25
7	January 5	2	14.75
8	January 9-10	6	88
9	January 10-11	4	43.75
10	January 11-12	2	22
11	January 12	2	9.25
12	January 14-15	3	45
13	January 17	4	16
14	January 17-18	4	31
15	January 21	2	12.75
16	January 25	5	44.75
17	February 2-3	4	75.5

Table 5-1
Storm Dates and Site Usage, 2023-2024 Winter Season

Storm Number	Storm Period	Number of CNGs Operated	Generator Hours
18	February 5	1	7.75
19	February 6-7	3	36
20	February 8-9	6	110.25
21	February 15	3	19
22	February 16	5	24.25
23	February 18	6	13
24	February 20-21	3	22
25	February 22	2	6
26	February 26-27	5	41.25
27	March 7	4	21
28	March 12	4	27.25
29	March 13	3	26.5
30	March 23	6	21.25
31	March 24	2	18
32	March 25	7	42
33	March 26	7	57.5
34	March 28	4	23
35	March 31 – April 1	6	68.5
36	April 5-7	5	128.75
37	April 15	3	29.75
Total	---	---	1321.75

Table 5-2
Generator Hours for 2023-24, Storms 1-10

Storm	1	2	3	4	5	6	7	8	9	10
	Nov 16	Nov 19-20	Dec 2-3	Dec 7	Dec 7-8	Dec 23	Jan 5	Jan 9-10	Jan 10-11	Jan 11-12
Baskin Reservoir	5	29.75				5		16		
Mountain Dell Treatment					10	4.25	7.25			
4500 S Pump House	5	12			16.5	5		16	15.5	11
White Reservoir	5	15.5			17	5		16		
Big Cottonwood			3	2			7.5	14	4.5	
Little Cottonwood Canyon			18					10		
Sandy Metro								16	18	11
Alpine			18						5.75	
Storm Total	15	57.25	39	2	43.5	19.25	14.75	88	43.75	22

Table 5-3
Generator Hours for 2023-24, Storms 11-20

Storm	11	12	13	14	15	16	17	18	19	20
	Jan 12	Jan 14-15	Jan 17	Jan 17-18	Jan 21	Jan 25	Feb 2-3	Feb 5	Feb 6-7	Feb 8-9
Baskin Reservoir		22							12	17.5
Mountain Dell Treatment		1				7.75	12.5			23.75
4500 S Pump House			4	6		11.5	21		12	5
White Reservoir		22				5	21		12	
Big Cottonwood	4.25		4	10.5		11				27.75
Little Cottonwood Canyon	5			9.5	6.75					29.25
Sandy Metro			4	5		9.5	21			7
Alpine			4		6			7.75		
Storm Total	9.25	45	16	31	12.75	44.75	75.5	7.75	36	110.25

Table 5-4
Generator Hours for 2023-24, Storms 21-30

Storm	21	22	23	24	25	26	27	28	29	30
	Feb 15	Feb 16	Feb 18	Feb 20-21	Feb 22	Feb 26-27	Mar 7	Mar 12	Mar 13	Mar 23
Baskin Reservoir		3.25	2			15		6.75		3.25
Mountain Dell Treatment			2		3	4.75	6		9	
4500 S Pump House		3.5	2	9		6	4	7	8	3
White Reservoir	6	6					6			
Big Cottonwood	7	5.5	2.5	10	3				9.5	4
Little Cottonwood Canyon		6	2.5			9.5	5	6		3.5
Sandy Metro	6		2	3		6		7.5		4
Alpine										3.5
Storm Total	**19**	**24.25**	**13**	**22**	**6**	**41.25**	**21**	**27.25**	**26.5**	**21.25**

Table 5-5
Generator Hours for 2023-24, Storms 31-40

Storm	31	32	33	34	35	36	37	Site Total
	Mar 24	Mar 25	Mar 26	Mar 28	Mar 31-Apr 1	Apr 5-7	Apr 15	
Baskin Reservoir		6.5	12					**156**
Mountain Dell Treatment	3.75	7.5	11	5	6	21	16	**161.5**
4500 S Pump House		6.5	8	6.5	12	22		**238**
White Reservoir		6.5	8		12	22		**185**
Big Cottonwood	14.25	4	10.5	5	13	36.75	4	**217.5**
Little Cottonwood Canyon		7	4		12.5	27	9.75	**171.25**
Sandy Metro		4	4	6.5	13			**147.5**
Alpine								**45**
Storm Total	**18**	**42**	**57.5**	**23**	**68.5**	**128.75**	**29.75**	**1321.75**

Snowfall for the 2023-2024 winter season was above the normal (median) values, averaging over 130% of the median as of the end of the seeding program in mid-April. Data for each SNOTEL site as of April 15 is shown in Table 5-6.

Table 5-6
Snowpack and Precipitation Data from SNOTEL sites – April 15, 2024

Measurement Site	Snow Water Equivalent (in)			Water Year Precipitation (in)		
	4-15-23	Median	%	4-15-23	Median	%
Louis Meadow	16.4	6.6	248%	33.0	22.5	147%
Lookout Peak	35.4	25.6	138%	37.5	30.9	121%
Parleys Summit	14.7	10.6	139%	27.1	22.8	119%
Mill-D North	32.7	22.0	149%	34.1	26.2	130%
Brighton	24.4	22.6	108%	30.8	26.2	118%
Snowbird	48.3	38.4	126%	43.9	35.6	123%
Basin Index %			133%			123%

Figures 5.1 to 5.4 show plots of data from three SNOTEL sites located in the target area during the 2023-2024 winter season, ending in mid May. Figure 5.4 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.

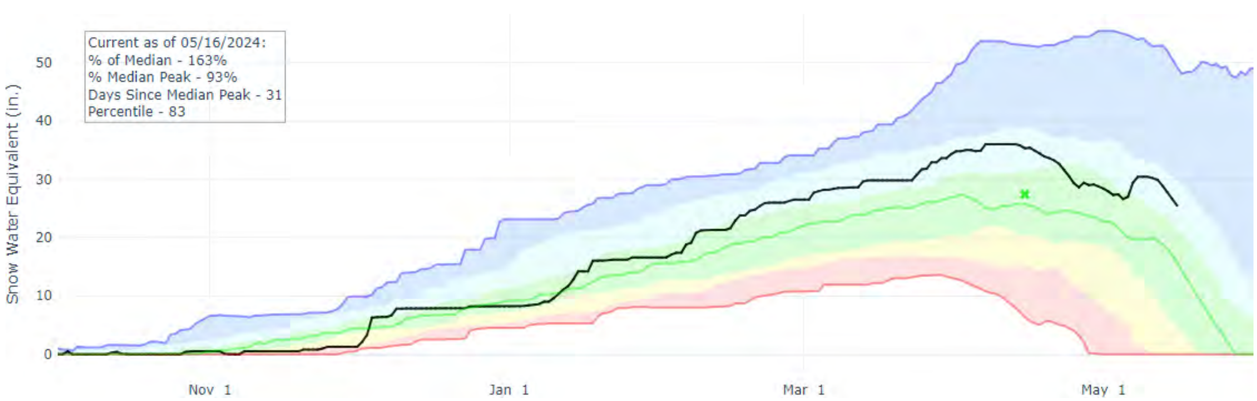


Figure 5.1. **NRCS SNOTEL snow and precipitation plot for Lookout Peak (8161 feet elevation). Historical max/min values shown as purple and red lines; median as green; current season as black.**

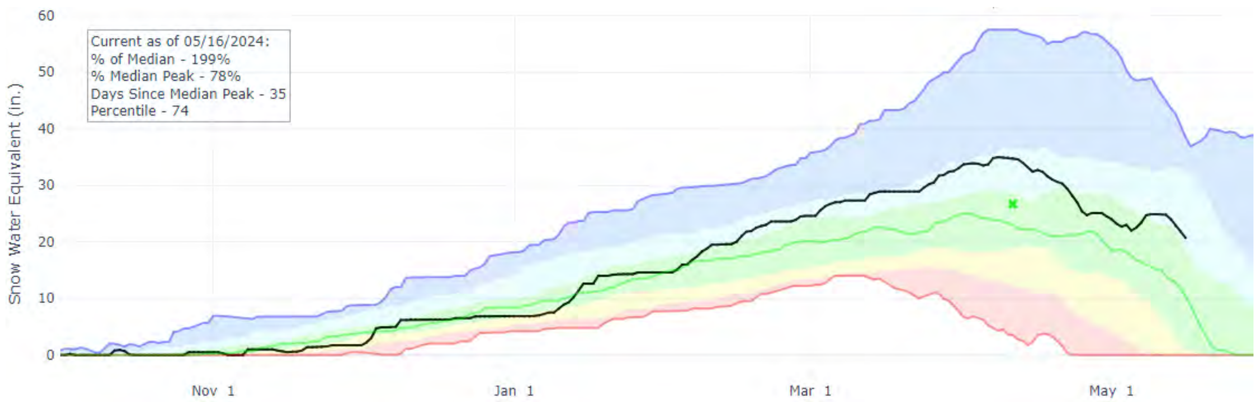


Figure 5.2. **NRCS SNOTEL snow and precipitation plot for Mill D – North (8963 feet). Historical max/min values shown as purple and red lines; median as green; current season as black.**

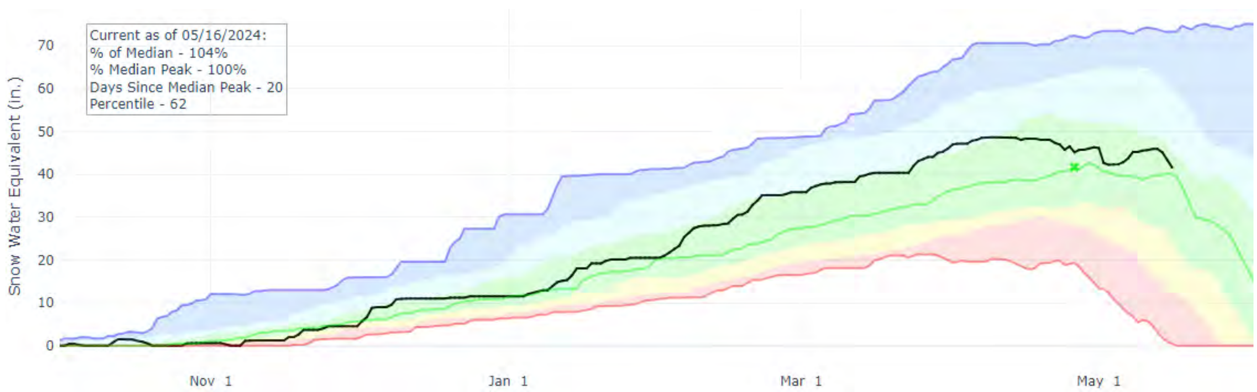


Figure 5.3. **NRCS SNOTEL snow and precipitation plot for Snowbird (9177 feet). Historical max/min values shown as purple and red lines; median as green; current season as black.**

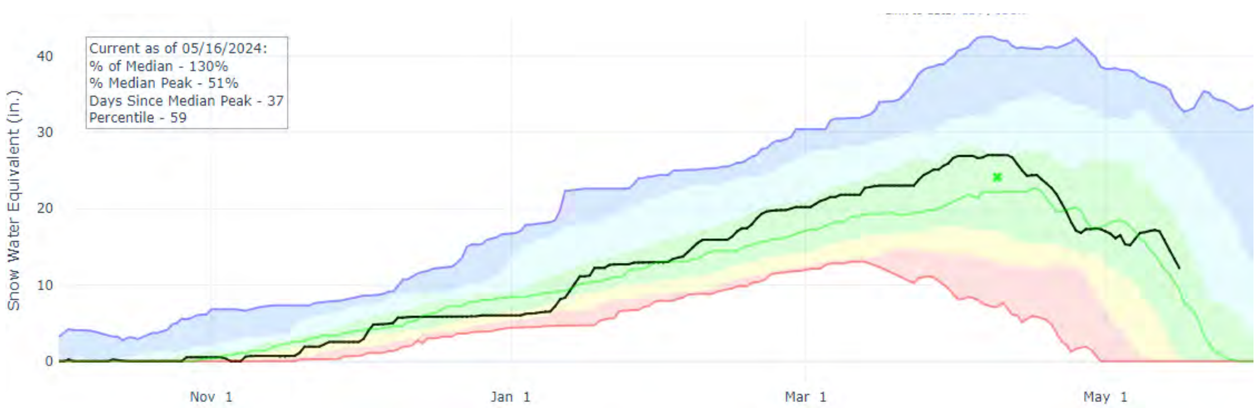


Figure 5.4 **NRCS SNOTEL snow and precipitation plot for Brighton (8766 feet). Historical max/min values shown as purple and red lines; median as green; current season as black.**

5.2. Operational Procedures

In operational practice, approaching storms were closely monitored by NAWC meteorologists utilizing online weather information. If the storm met the seedability criteria presented in Table 3-1, 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; for example, a northwesterly wind would be blowing from the northwest toward the southeast.

5.3. Operational Summary

This section summarizes the weather conditions and seeding operations during the season's storm events. All times are local (MST/MDT) unless otherwise noted.

November 2023

November had below average precipitation (Figure 5.5) and only two seeded events for the Six Creeks program.

Some light showers and marginal temperatures on November 16, with winds shifting to the northwest by midday and as well as some weak convective type clouds, produced somewhat suitable conditions for seeding during the late morning to mid afternoon hours. Much of the moisture was of subtropical origin but a shortware trough moving across the area produced enough cooling and mixing for some seeding operations. Precipitation amounts were about a half inch to an inch for the storm event as a whole.

A compact and vigorous trough moved southeastward across the Great Basin on November 19. The 700 mb temperature dropped to below -8° C in the Six Creeks area after midday with winds becoming northwesterly, then almost due northerly by the night of November 19-20. Seeding was conducted during the daytime hours on the 19th at several sites, and continued until the afternoon of November 20 at a couple of sites with some lingering snowfall in a cold advection northerly flow pattern. Precipitation totals for the event as a whole ranged from about 0.6 – 1.4 inches of water equivalent.

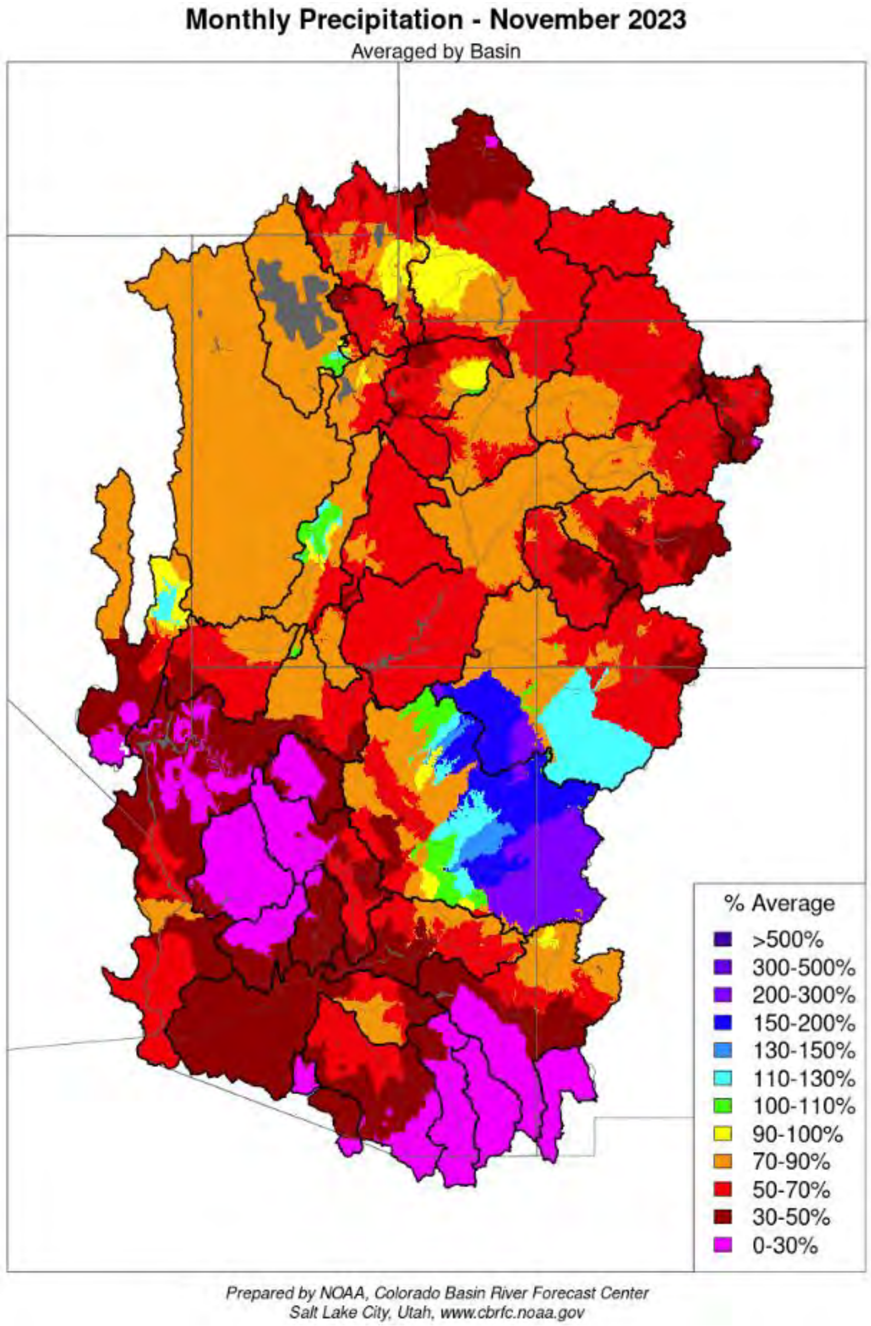


Figure 5.5 November 2023 precipitation percent of average (median)

December 2023

December was another relatively dry month for the Six Creeks area, although the basin was in a sharp gradient between near to locally above average precipitation in far northern Utah and much drier conditions over central and southern Utah (Figure 5.6). There was three seeded storm periods for the Six Creeks program in December.

Some seeding was conducted midday on December 7 with brief shower activity midday into the afternoon following a fast-moving cold frontal passage. 700 mb temperatures dropped to around -8° C. Another cold front followed right after it, on the night of December 7-8 with additional snowfall and temperatures dropping further to around -13° C at 700 mb by the 8th. Seeding continued until about sunset on December 8, with orographic and convective snow shower activity through the daytime hours. Precipitation totals for the December 7-8 period ranged from about 0.6 inches to locally as much as 2.0" of water equivalent in the Cottonwood Canyons, which were highly favored by orographics effects in the northwesterly wind pattern and received heavy snowfall.

After a period of dry weather and valley temperature inversions during much of December, a cold front and band of snow moved across the area on December 23 with significant cooling. The 700 mb temperature dropped to around -13° C by later in the day with winds becoming northwesterly. Seeding was conducted in the morning to midday hours with the main band of snow, with only a few light snow showers following into the early afternoon at which time seeding ended. Precipitation totals were in the 0.3 – 0.7 inch range of water equivalent with this storm event.

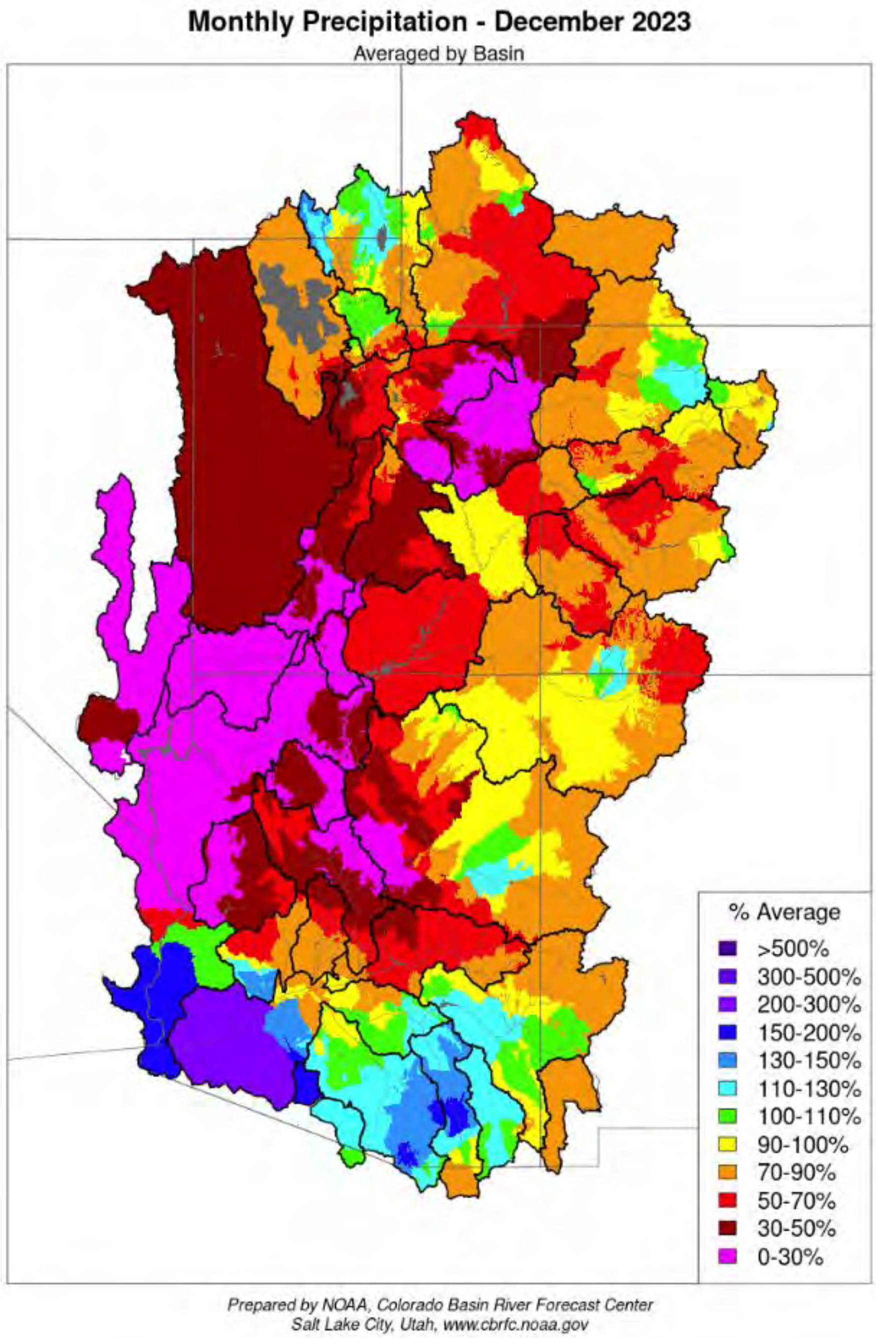


Figure 5.6 **December 2023 precipitation, percent of average**

January 2024

The relatively dry weather pattern in December carried over for only a few days into January, before the pattern changed and became more active. For the month as a whole, snowfall and precipitation ended up being above average for most of Utah (Figure 5.7). Beginning with the first seeded event on January 5, there were a total of 10 seeded storm periods for the Six Creeks program in January.

A weak storm event resulted in limited seeding during the daytime hours on January 5, with a 700 mb temperature near -11° C and fairly low cloud liquid water content. There were a few lower clouds observed at times, and a few inches of snowfall occurrred in the Wasatch Range. Seeding ended around sunset, with precipitation totals in the range of 0.2 – 0.6 inches of water equivalent.

A fast-moving cold front brought a squall line with strong winds and a brief period of heavy snowfall late on January 9. Seeding began in the early evening and continued through the night, ending on the morning of January 10. Most of the cloud liquid water with this system was likely concentrated in the cold frontal squall line. Precipitation totals were in the 0.5 – 1.0 inch range (water equivalent).

After some lake enhance snow showers began on the night of January 10-11 in a very cold atmosphere (700 mb temperature near -18° C), snowfall continued at times on January 11. While these clouds were essentially all ice and lack liquid water, warm advection resulted in at least model forecasts of some liquid water by late on January 11 and a couple of seeding sites were operated overnight (January 11-12). Visual observations indicated a cloud base near 8,500 feet containing at least some liquid water overnight. By the morning of January 12, observations again showed a quite cold atmosphere (700 mb near -17° C at SLC) and lack of liquid water along with increasing winds, so ended seeding operations at that point. With a very cold arctic trough to the north of the area and some moisture moving around the base of this trough, moisture values increased just enough by the afternoon and evening of January 12 for another brief period of seeding near the Cottonwood Canyons as the 700 mb temperature warmed somewhat to near -12° C. However, winds were quite strong in some areas which also made targeting difficult. Precipitation totals for the January 11-12 period as a whole were mostly around a half inch or less of water content.

The next storm in a series affected the area beginning on January 13, with a cold arctic air mass in the lower levels of far northern Utah just north of the SLC area and a much milder and moist system moving in from the west and southwest. Winds and other conditions, however, remained unfavorable for operations with a warm advection pattern overnight (January 13-14). Winds shifted to light northwesterly during the day on January 14 with much higher moisture values in the lower levels. Some banded, orographic type snow showers developed and continued overnight (January 14-15) with seeding operations during this time period. The 700 mb temperature was near -8° C. Precipitation totals for the seeded period of this event (January 14-15) were essentially in the 0.5 – 1.0 inch range of water content. Seeding ended on the morning of the 15th with clearing skies. Ski resorts in the Wasatch reported as much as 30-40 inches of snowfall from the January 13-15 time period as a whole.

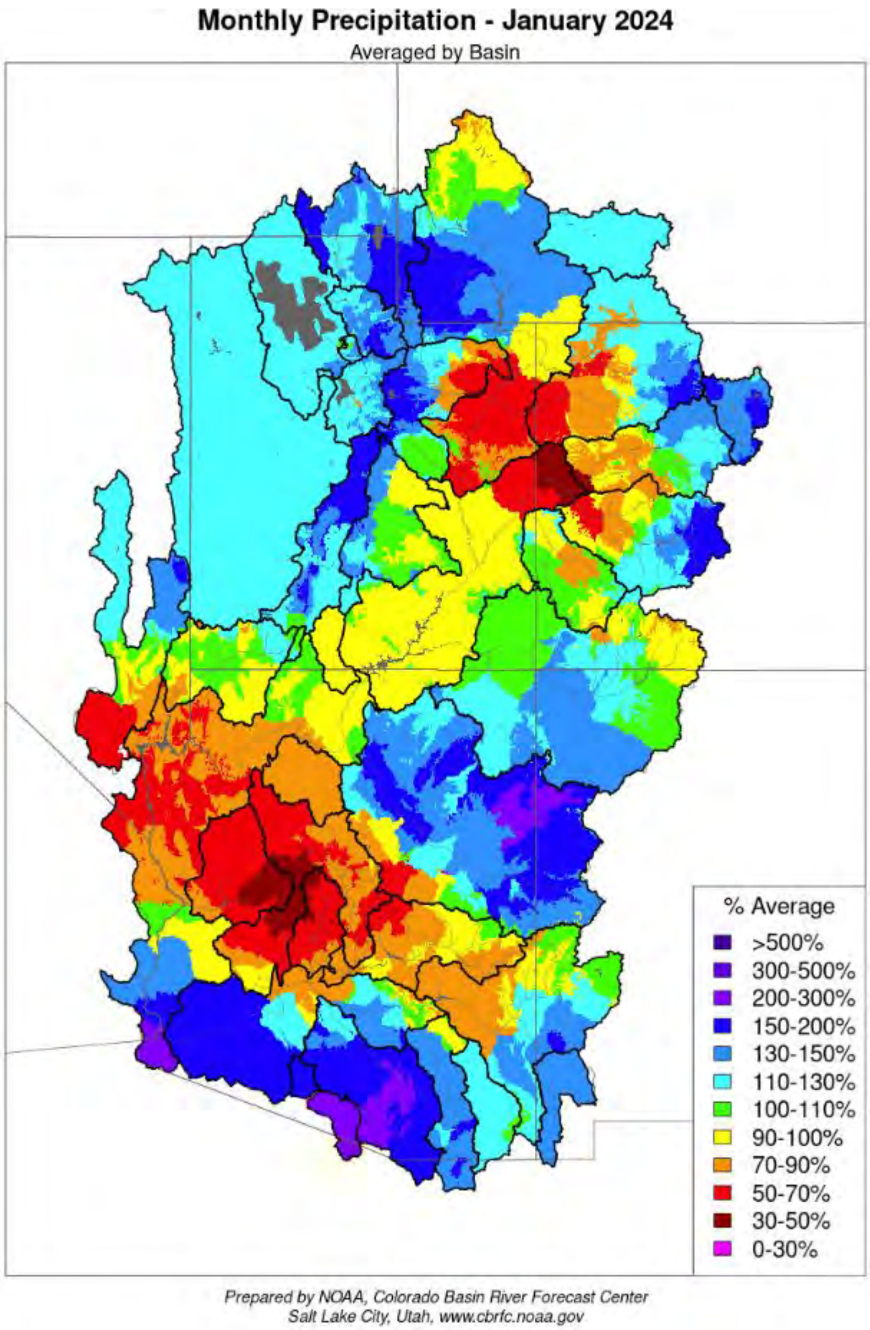


Figure 5.7 January 2024 precipitation, percent of average

A complex situation developed on January 17-18 with a mix of warmer air aloft and some lower-level cold air just north of SLC on the morning of the 17th. This resulted in valley rain initially, with seeding operations in the morning to midday at which point valley precipitation turned to snow due to a low level cold air mass that also limited seeding operations. There was some seeding during this time period, as well as overnight (January 17-18) again as moist lower levels combined with light northwesterly winds produced at least a limited seeding opportunity. Precipitation totals of about 0.7 – 1.2 inches water content occurred, most of this during the day on the 17th. Seeding operations ended by the morning of the 18th.

A mild and moist air mass on January 21 provided a seeding opportunity during the midday through afternoon hours with some liquid water clouds over the Wasatch. Temperatures were somewhat warm, above -5° C at 700 mb with fairly light valley winds which limited targeting options. A couple of sites were used to target the southern portion of the Six Creeks target area, with mostly light precipitation totals of 0.1 – 0.3 inches water equivalent.

A trough moving from Oregon across Idaho and the northern Great Basin provided a seeding opportunity during the day on January 25, with some sites running until about midnight overnight after which point snowfall ended. Precipitation was mostly light with some valley rain/drizzle and mountain snow, and a 700 mb temperature near -8° C. Precipitation totals in the Six Creeks area were in the 0.2 – 0.5-inch range of water content.

February 2024

The weather pattern in February was consistently active and wet, with much above normal precipitation/snowfall and in fact close to double the monthly normal (median) values at some SNOTEL sites. This wet pattern affected most of the state as seen in Figure 5.8. There were 10 seeded storm periods for the Six Creeks program in February.

A fairly weak trough axis developed over the area on February 2, but cooling temperatures along with precipitation in westerly flow resulted in seeding operations beginning around midday. Winds become northwesterly with a 700 mb temperature near -8° C by the night of February 2-3, and seeding continued overnight. Some intermittnet convective snow showers continued during the day on February 3 although these were under-forecast by the models and seeding ended on the morning of the 3rd. This storm event brought water content amounts ranging between a half inch to 1.5 inches of water content to the Six Creeks area.

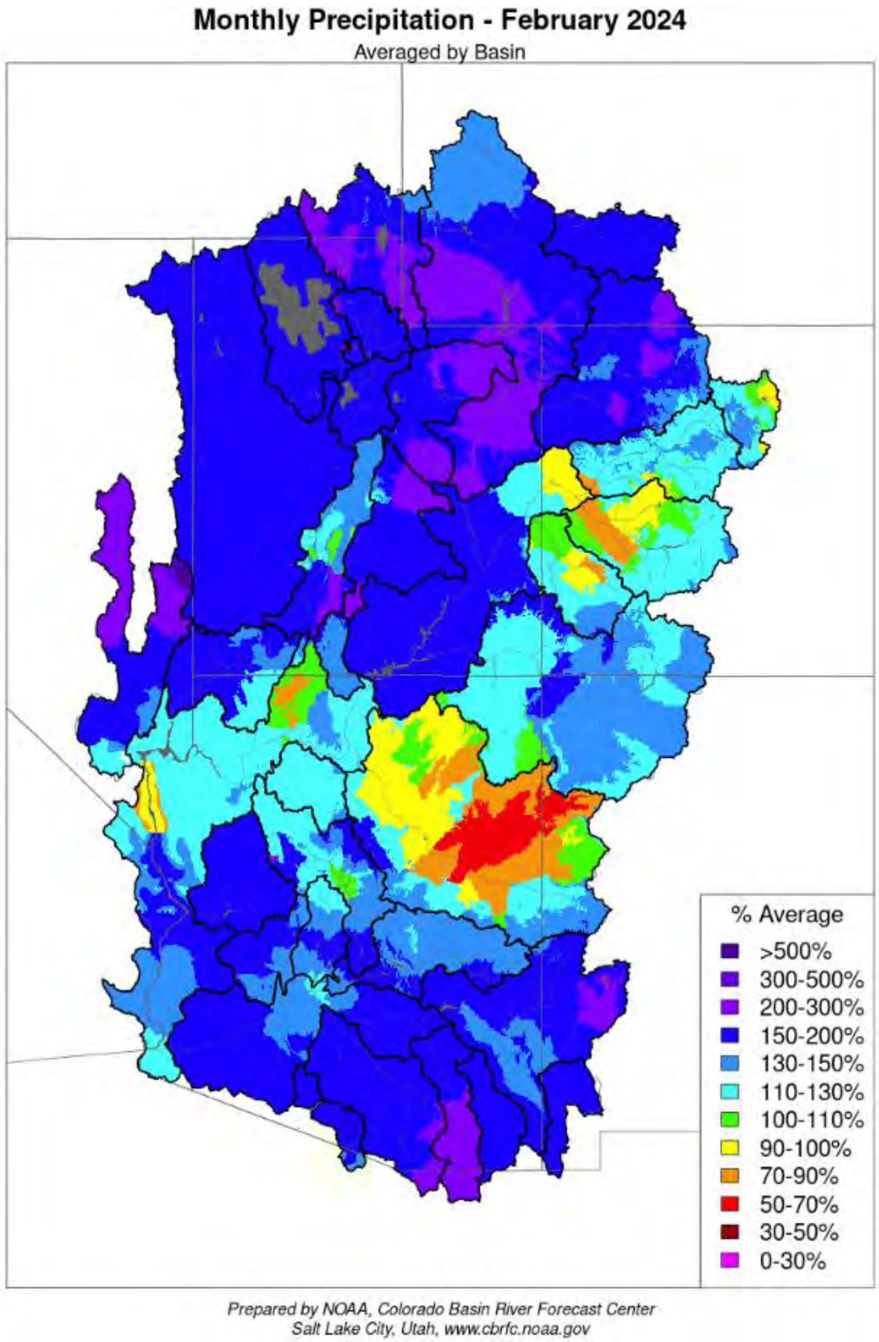


Figure 5.8 **February 2024 precipitation, percent of average**

A subtropical moisture plume in mostly southerly flow on February 5 had somewhat marginal temperatures for seeding, near -4° C at 700 mb. However, atmospheric mixing appeared good and seeding was conducted at the Alpine site during the daytime hours. Winds were not favorable for use of other sites. Precipitation amounts ranged from about 0.4 – 1.0 inches of water equivalent.

Another surge of subtropical moisture into Utah on Feburary 6 was associated by a the core of a complex trough moving from southern California on the 6th, across Arizona and Utah on February 7. While conditions were initially too warm for seeding, the 700 mb temperature cooled to around -6° C by February 7 with southwesterly flow. Seeding was conducted mostly overnight February 6-7 and during the day on the 7th, with seeding ending on the evening of February 7 as showers gradually tapered off and valley winds become light. Precipitation totals were quite significant partially due to the subtropical moisture associated with this system, with SNOTEL sites in the Six Creeks area receiving between about 0.9 – 2.2 inches of water content from the storm event as a whole.

Orographic and diurnal (daytime heating inducted) snow showers occurred during the February 8-9 time period with a weak trough over the region. The 700 mb temperature was near -10 to -12° C with mostly southwesterly winds. Seeding was conducted both days as well as overnight February 8-9, with a significant amount of seeding hours and preciptiation totals for this time period ranging from about 0.6 – 1.4 inches of water content in the target area.

A weakening trough on February 15 brought rain/snow across the area mostly in the morning to midday hours, with a 700 mb temperature near -7 to -8° C. It was followed by some trailing showers into the mid-afternoon hours. Seeding was conducted at a few sites from about mid-morning into the afternoon, with precipitation totals generally in the 0.6 – 1.3 inch range of water content for the Six Creeks area.

A trough over the Pacific Northwest was moving into the northern Rockies states on February 16, with some arctic air wrapping into the trough as well just to the north of Utah. Bands of snow shower activity and snow squalls developed as winds became northerly during the afternoon and evening hours, with some showers containing graupel which is a good indication of significant liquid water. Seeding was conducted from the early afternoon to early evening hours. The 700 mb temperature dropped to around -10° C by the evening hours, with precipitation and seeding ending in the evening. SNOTEL sites in the Six Creeks area received between about 0.5 – 1.3 inches of water content from this storm event.

A fairly weak trough pushed a cold front across northern Utah on February 18, with rain/snow beginning in the morning followed by convective showers in the afternoon as winds shifted to the northwest at lower levels. Seeding was conducted during the afternoon and evening hours, as the 700 mb temperature dropped to near or below -5° C and convection developed. Precipitation totals ranged from about 0.3 – 0.7 inches of water equivalent with several inches of snow accumulation in the Six Creeks area.

A plume of moisture on February 20 was accompanied by warm temperatures in southerly flow. Seeding began at the southern (Alpine) site on the night of February 20-21 and then from the Salt Lake Valley sites on the 21st with somewhat colder temperatures (near -5 to -6° C) and some convective showers in westerly flow. A solid lower-level cloud deck persisted into the evening of February 21 with some upstream snow showers, but these were weakening and expected to dissipate per forecast model data, and valley winds were becoming light. Seeding ended by late evening on the 21st, with storm event precipitation totals for February 20-21 ranging between about 0.7 – 2.3 inches of water equivalent. Much of this occurred in warm, early portion of the storm although a good deal in the seeded portion as well.

There was some brief seeding during the early afternoon on February 22 as daytime heating initiated some convective snow showers in a relate lively cool, moist air mass. The 700 mb temperature was around -8° C with northwesterly winds. Seeding was conducted for a few hours at a couple of sites, with light precipitation amounts near 0.1 inch at most sites.

A large, cold trough moved onshore in the Pacific Northwest on February 26, bringing a cold front across the Six Creeks area overnight (February 26-27). Seeding was conducted overnight with this frontal passage, and into the morning of February 27 with lingering snow showers. Clouds become pretty icy due to very cold temperatures, near -17° C at 700 mb, on the 27^{th} and seeding operations ended before midday. Precipitation totals were mostly in the 0.4 – 1.0-inch range at SNOTEL sites with this event.

March 2024

March was another active weather month across the region with frequent storm events and above average precipitation/snowfall (Figure 5.9). This brought snowpack in the Six Creeks area to well above average, roughly 135% of the median by April 1. There were nine seeded storm periods in March.

A weak trough over the region on March 7 produced some fairly light showers. The 700 mb temperature was near -7° C with cloud bases near the freezing level, around 7,000 feet elevation. Some weak convective and orographic showers developed although they were pretty limited in depth with winds becoming northwesterly below the 700 mb level. Seeding was conducted from several sites from late morning until early evening, with precipitation totals between about 0.3 – 0.6 inches of water content.

A cold trough over the Pacific Northwest on March 12 subsequently moved into the Great Basin on March 13. The first seeded period occurred with a frontal precipitation band on the afternoon and evening of the 12^{th}, with the 700 mb temperature falling to around -7° C as the front moved through and winds shifted to the northwest. Seeding was conducted from several sites, ending late in the evening with a break in precipitation activity overnight. Precipitation amounts in the 0.7 – 1.5-inch range of water equivalent were recorded with the frontal passage.

Snow showers developed in a cold northwesterly wind pattern on March 13, aided by surface heating and cold air aloft (-10 to -12° C at 700 mb). A few to locally several more inches of snowfall occurred in the Six Creeks area with water content between about 0.2 – 0.5 inches. Seeding was conducted from a few sites during the morning and afternoon hours, with snow showers ending by about 1700 MDT.

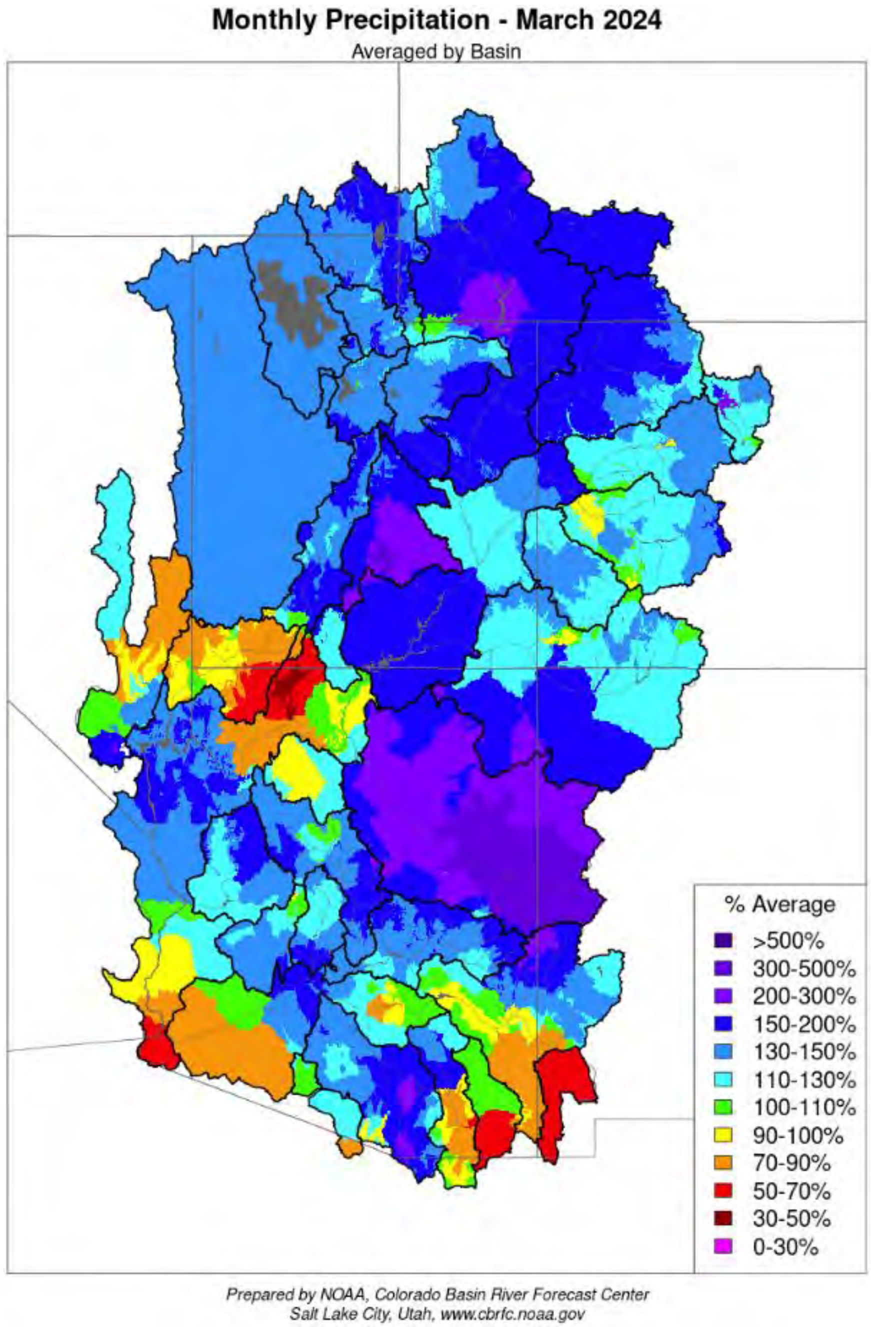


Figure 5.9 **March 2024 precipitation, percent of average**

A large and cold trough brought a period of stormy weather and additional seeding opportunities each day during the March 23-26 period, with an initial cold frontal passage seeding on the evening of March 23. The 700 mb temperature dropped to below -6° C behind the cold front, with the snow level falling to around 5,000 feet or lower by late evening. Seeding was conducted for a few hours from a good number of sites during this frontal passage, with precipitation (water content) in the 0.5 - 1.2 inch range.

A large trough over the region produced a cold, moist northwesterly wind pattern on March 24 (700 mb temperature around -8° C). Seeding was conducted through the daytime hours with scattered snow showers and thundershowers developing which contained some graupel and good liquid water content. There were also some lake effect or lake enhanced showers especially in the morning. Precipitation far exceeded the forecast amounts, with about 0.4 – 0.8 inches of water content in the Six Creeks area.

A similar pattern continued on March 25-26 to that of the 24th, with seeding during the daytime hours to target scattered convective showers and some lake effect snow shower activity. 700 mb temperatures were near -8 to -10° C in northwesterly flow. Precipitation amounts ranged from about 0.1 – 0.4 inches of water content on the 25th and 0.3 – 0.7 inches on the 26th.

Another large trough centered off the Pacific Northwest coast brought a frontal passage to the Six Creeks area during the afternoon/evening of March 28. A good frontal precipitation band was noted with the 700 mb temperature dropping to around -7° C behind the front. Seeding was conducted at several sites from the early afternoon to early evening hours, with drying later in the evening. Precipitation totals ranged from about 0.4 – 0.8 inches of water equivalent.

Another large trough moving onshore near California brought some precipitation in southerly flow on March 30-31. Although temperature was warm initially and wind direction precluded much of any seeding opportunity, winds shifted to the northwest late on March 31 and temperatures cooled into a favorable range. Seeding was conducted beginning midday on the 31st (although evening at most sites) and continued overnight, ending at most sites on the morning of April 1 although continuing at one site until evening. Winds become due northerly on April 1 which favored only the site in Parley's Canyon for continued seeding. Precipitation for this storm period ranged from about 0.6 – 1.5 inches of water content at SNOTEL sites.

April 2024

April was a drier than average month (Figure 5.10), with a couple of additional seeded events prior to the Six Creeks program ending for the season on April 15.

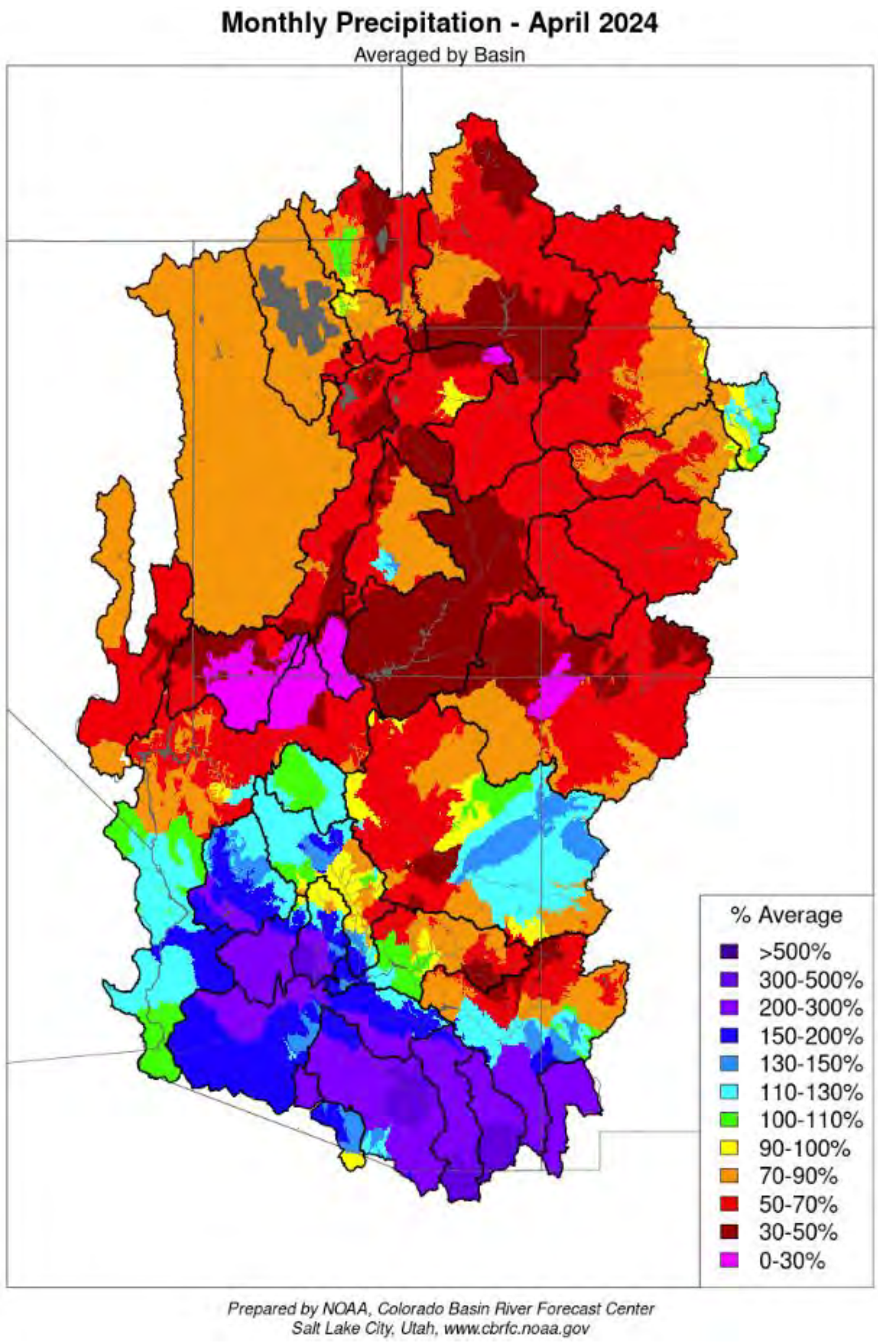


Figure 5.10 April 2024 precipitation, percent of average

A deep trough moved eastward from California early on April 5 into the Great Basin on April 5-6. This complex system developed several circulation centers, with an initial cold front arriving from the southwest (somewhat atypical) on April 5 with limited moisture intially. Seeding began at some favorable sites on the evening of April 5 in southwest flow with more added on April 6 as winds became northwesterly and temperatures quite cold. The 700 mb temperature dropped to below -10° C with this event, bringing snow levels down to the lower valleys. Northwesterly flow produced areas of heavy snow showers, including some lake enhanced snowfall activity on April 6, with about a foot of new snow falling in the Cottonwood Canyons during the day from this activity. These showers were visually impressive with good instability aloft despite relatively low moisture content of the lower atmosphere. Although snowfall was generally expected to end on the night of April 6, some snow showers lingered into the night with good convective and orographic cloud structures so kept seeding going, ending early on April 7. Precipitation totals for this storm period ranged from 0.5 – 1.0 inches of water content in most of the Six Creeks area, occurring primarily during the day on April 6.

The final seeded event of the season occurred on April 15, with a trough producing semi-convective shower activity and a 700 mb temperature near -5° C. Showers continued in northwesterly flow, with seeding during the daytime hours, mostly ending by late evening. Seeding continued at one site in Parley's Canyon into the night and was counted up until midnight. Temperatures began to warm overnight (April 15-16) with light valley winds which reduced seeding potential from the lower valley despite some ongoing showers. The Six Creeks area received around 0.3 – 0.6 inches of water content from this event.

6. 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% 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 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, 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 gauges 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 past and current seeded seasons (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 considered an external data set for these more recent evaluations, and considered separately from the recent seeded season data during the current program.

6.2. Evaluation Approach

The state of Utah (as well as many other western 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. 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 specified time period, 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 subject to some 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 snowpack (SWE) equations have slightly lower correlations and the results may be less reliable than those produced by the corresponding precipitation analyses.

Figure 6.1 shows a map of the target area and the five target SNOTEL sites, while Figure 6.2 shows the 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 five 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 SNOTEL) and a couple of sites in eastern/northern Nevada, Berry Creek and Pole Creek, were selected as controls. The two Nevada sites are also utilized as controls for other Utah seeding programs. A SNOTEL site (Cascade) located 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 final selection of the three control sites shown in Figure 6.2 should be ideal for producing a realistic forecast of “natural” target area precipitation for comparison to the observed values during the seeded seasons. SNOTEL sites located inside the Six Creeks target area are utilized as the set of target sites.

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 (feet)
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 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 6-2.

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 1st snow water content, and X = control 3-site average, X_1 = Farmington, X_2 = Berry Creek, NV and X_3 = Pole Creek, NV

6.4. Historic Evaluation Data

For the 2024 winter season the State of Utah and local sponsors significantly expanded seeding along the Wasatch front. Many of the SNOTEL sites used as non-seeded "control" sites for the seasonal evaluations are now in areas targeted by seeding operations. This includes the Farmington Canyon SNOTEL, which was by far the best control site for the Six Creeks program's evaluations. As such, target vs control evaluations will no longer be performed on an annual basis. Rather, the average result of the historic target vs control studies (evaluating the predicted increase in snowpack and precipitation) for Six Creeks program area will be used to derive the estimated increases in streamflow resulting from cloud seeding in a given season.

The historic studies, over both seeding periods (1989-1996 and 2019-2022, as referenced above) are indicative of an average increase in snowpack and seasonal precipitation resulting from cloud seeding of roughly 6%.

For a detailed explanation of these historic results please reference the 2022-2023 cloud seeding report. This result is in line with the derived increase estimates for neighboring programs, with much longer periods of uninterrupted cloud seeding and larger target vs control data sets.

6.5. Determining the Impact of Cloud Seeding on Streamflow

To better understand the value and impact of a cloud seeding program, research has been conducted every year to estimate the increase in runoff that occurs because of cloud seeding. This analysis is accomplished, first, by tabulating actual snowpack and seasonal precipitation values for the seeded period. Second, using the aforementioned results from the long-term target control study, predicting the increase in SWE and precipitation (measured value) that resulted from cloud seeding. Third, analyzing the relationship between snowpack/precipitation and runoff for the watershed and defining that relationship with a mathematical regression. Fourth, using the new regression (correlating snowpack/precipitation and streamflow) to determine how much a 6% increase to the natural snowpack and precipitation would have contributed to streamflow, on average, for the seeded seasons.

This form of analyses does require that runoff be measured in largely unregulated waterways, not downstream from a reservoir with heavily controlled discharge rates. In the case of relatively small diversions (such as for city water use or local agriculture) upstream from the gauge, a strong correlation between snowpack/precipitation and runoff may be found. However, the larger the upstream diversion, the more prone to inaccuracies the results will be due to errors that arise in upscaling.

6.6. Results – Impact of Cloud Seeding on Runoff

Streamflow gauges used to derive runoff increases for this program are located on Little Cottonwood Creek (USGS gauge 10168000, Little Cottonwood Creek at the Jordan River) and at Red Butte Creek. Streamflow totals (generally reported in acre-feet) are collected for the March – July period. This period tends to produce the highest correlation to wintertime snowpack and precipitation. Regression equations having a good correlation (generally, an R value of about 0.80 or higher) should be reasonable for this analysis. In the case of Little Cottonwood Creek, both streamflow and corresponding SNOTEL data was available beginning in 1999, and for Red Butte Creek back to 1989.

For Little Cottonwood Creek, the streamflow gauge correlated well with both the Snowbird and Brighton SNOTEL precipitation (Nov-Apr), with an R value of around 0.87 for each. An average of the two sites improved it slightly to 0.88. For snowpack (Apr 1), the best correlation was to the Brighton SNOTEL (R = 0.84) with a somewhat lower correlation to Snowbird. In the headwaters area of Red Butte Creek, the Lookout Peak SNOTEL site has the longest record (back to 1989) and there is a reasonably good correlation between this site's seasonal precipitation data and resulting streamflow (R = 0.84). Snowpack data at Lookout Peak had a lower correlation to Red Butte streamflow (R = 0.77).

Utilizing these equations for Little Cottonwood Creek, a 6% increase in April 1 snowpack yielded an estimated 8.4% increase to streamflow and a 6% increase to November – April precipitation yielded an estimated 13.5% increase in streamflow. The average (base) streamflow at this gauge is over 24,000 AF.

These equations predict an additional 2060 and 3290 AF, respectively, in increased runoff resulting from cloud seeding in Little Cottonwood Creek.

For Red Butte Creek, a 6% increase to seasonal (November – April) precipitation at the Lookout Peak SNOTEL site results in an estimated 15.1% increase in streamflow. The base streamflow value for this site is, much lower, with an average over just over 1,700 AF (March -July) for the analysis period. These results, therefore, predict an increase in runoff of just over 250 AF for Red Butte Creek resulting from cloud seeding.

The results for the Little Cottonwood and Red Butte Creeks collectively provide a good indication of the impact on cloud seeding in this watershed. With relative confidence the data suggests that cloud seeding results in an 8-12% increase in runoff across all major runoff channels in the 6-creeks target area. It should be noted that drier portions of a watershed produce less efficient runoff, and seeding may therefore generate higher **percentage** increases to streamfow in such areas. The typically somewhat lower percentage runoff increases pertaining to the wetter (most productive) portions are likely the most accurate for application to the watershed as a whole, if a percentage increase is scaled to the entire watershed. In either case, a higher **percentage** increase to streamflow (than the seasonal percentage increase to precipitation/snowpack) is an expected result as seen in these evaluations.

APPENDIX A: SUSPENSION CRITERIA

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

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

1. Excess snowpack accumulation

2. Rain-induced winter flooding

3. Severe weather

Excess Snowpack Accumulation

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

Project & Basin	Critical Streamflow Volume (Acft) & USGS Streamgage	SNOTEL Station	SWE Value Corresponding to the Critical Flow								Ranking of SNOTEL Stations
			Jan 1 (in.)	Jan 1 (%)	Feb 1 (in.)	Feb 1 (in %)	March 1 (in.)	March 1 (in %)	April 1 (in.)	April 1 (in %)	
1. Northern Utah	185,208	Franklin Basin, Idaho	19.50	190.84	27.14	165.31	34.35	154.71	41.56	153.60	1
Logan at Logan	USGS 10109000	Tony Grove	28.73	205.94	39.44	175.56	48.06	160.38	56.34	156.56	2
		Bug Lake	17.08	218.82	21.91	180.34	26.72	165.25	31.65	162.70	3
		Average	**21.80**	**205.20**	**29.50**	**173.70**	**36.40**	**160.10**	**43.20**	**157.60**	
Weber near Oakley	176,179	Chalk Creek #1	10.09	173.13	14.73	153.66	28.77	149.85	34.15	143.41	1
	USGS 10128500	Trial Lake	20.15	207.44	26.33	180.55	33.55	173.27	38.54	162.28	2
		Smith Morehouse	10.06	186.34	13.69	137.60	17.36	146.32	21.17	160.26	3
		Hayden Fork	12.19	194.16	16.69	172.11	20.71	158.56	21.79	164.64	4
		Average	**13.10**	**190.30**	**17.90**	**166.00**	**25.10**	**157.10**	**28.90**	**157.70**	
Dunn Creek near the Park Valley	5,733	George Creek	17.84	187.75	18.32	143.81	28.93	163.43	34.61	153.77	1
	USGS 10172952	Howell Canyon, Idaho	28.71	279.96	38	223.24	44.59	205.98	50.46	191.65	2
		Average	**23.30**	**233.90**	**28.20**	**183.60**	**36.80**	**184.70**	**42.60**	**172.70**	
2. Western & High Uintah	166,861	Lily Lake	11.38	202.70	16.40	194.06	17.69	147.37	28.93	139.19	1
Bear River near Utah - Wyoming state line	USGS 10011500	Trial Lake	20.07	206.54	26.56	182.26	33.68	173.94	38.49	162.05	2
		Hayden Fork	12.41	197.65	17.06	175.83	21.03	160.98	20.90	146.02	3
		Average	**14.60**	**202.30**	**20.00**	**184.10**	**24.10**	**160.80**	**29.40**	**149.10**	
Duchesne near Tabiona	140,976	Strawberry Divide	6.92	239.23	10.87	199.25	26.77	178.78	29.75	179.05	1
	USGS 09277500	Daniels-strawberry	16.07	248.12	21.59	202.44	27.82	190.54	29.89	192.75	2
		Smith Morehouse	10.61	196.64	14.95	172.41	18.82	158.83	22.22	168.26	3
		Rock Creek	8.76	230.02	12.31	219.65	15.88	205.68	16.41	209.06	4
		Average	**10.60**	**228.50**	**14.90**	**198.50**	**22.30**	**183.50**	**24.60**	**187.30**	
Provo near woodland	183,845	Trial Lake	22.98	236.53	27.78	190.63	35.23	181.59	31.44	132.39	1
	USGS 09277500	Beaver Divide	10.29	210.39	14.11	179.49	17.45	170.83	20.18	200.3	2
		Average	**16.70**	**223.50**	**20.90**	**185.10**	**26.30**	**176.20**	**25.80**	**166.40**	
3. Central & Southern	120,473	Castle Valley	12.23	244.05	16.96	203.04	22.22	187.68	26.30	180.00	1
Sevier near Hatch	USGS 10174500	Harris Flat	8.71	298.76	15.25	273.59	24.16	222.99	21.15	209.77	2
		Farnsworth Lake	17.25	218.10	20.96	185.95	27.05	182.24	32.93	167.03	3
		Average	**12.80**	**253.70**	**17.70**	**220.90**	**24.50**	**197.70**	**26.80**	**185.60**	
Coal Creek near Cedar City	38,533	Midway Valley	20.89	215.65	29.12	194.04	35.89	176.99	42.29	167.97	1
	USGS 10242000	Webster Flat	13.57	232.46	18.70	197.95	24.30	184.64	24.93	181.12	2
		Average	**17.20**	**224.10**	**23.90**	**196.00**	**30.10**	**180.90**	**33.60**	**174.60**	
South Willow near Grantsville	5,426	Rocky Basin-settlemnt	19.09	205.33	23.75	174.14	32.11	171.39	40.01	167.51	1
	USGS 10172800	Mining Fork	16.31	243.66	20.74	177.04	27.81	171.79	32.19	168.74	2
		Average	**17.70**	**224.50**	**22.30**	**175.60**	**30.00**	**171.60**	**36.10**	**168.10**	
Virgin River at Virgin	151,286	Kolob	23.11	229.25	29.08	220.78	36.51	197.43	43.71	196.21	1
	USGS 09406000	Harris Flat	9.71	377.00	15.69	304.18	21.46	300.00	20.11	370.00	2
		Midway Valley	24.76	256.17	34.56	238.40	41.44	209.68	51.05	211.06	3
		Long Flat	9.38	265.88	13.54	286.16	19.20	286.18	18.91	187.00	4
		Average	**16.70**	**282.10**	**23.20**	**262.40**	**29.70**	**248.40**	**33.40**	**241.10**	
Santa Clare above Baker Reservoir	11,620	Gardner Peak	13.00	293.90	16.82	172.15	21.70	167.36	24.45	163.95	1
	USGS 09409100	**Average**	**13.00**	**293.90**	**16.80**	**172.10**	**21.70**	**167.40**	**24.50**	**164.00**	
Utah State Average (%)				**230**		**197**		**183**		**178**	
Standard Deviation				**42**		**38**		**35**		**42**	
Upper 95%				**248**		**213**		**199**		**196**	
Lower 95%				**212**		**180**		**168**		**160**	

Snowpack-related suspension considerations will be assessed on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne River, Price-San Rafael, Dirty Devil, South Eastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. 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. There are a number of SNOTEL stations in the various basins of central and southern Utah on which these criteria are based. These include Castle Valley, Harris Flat, and Farnsworth Lake in the Sevier Basin; Midway Valley, Kolob, Harris Flat, Webster Flat, and Long Flat in southwestern Utah; and Rocky Basin Settlement and Mining Fork in eastern Tooele County.

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

Rain-induced Winter Floods

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

Severe Weather

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

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

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

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

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

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