Cloud Seeding Annual Report and Evaluation

Six Creeks Program
2022-2023 Winter Season

Prepared For:

Salt Lake City Department of Public Utilities

Utah Department of Water Resources

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WEATHER MODIFICATION

THE SCIENCE OF CLOUD SEEDING

The Science

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

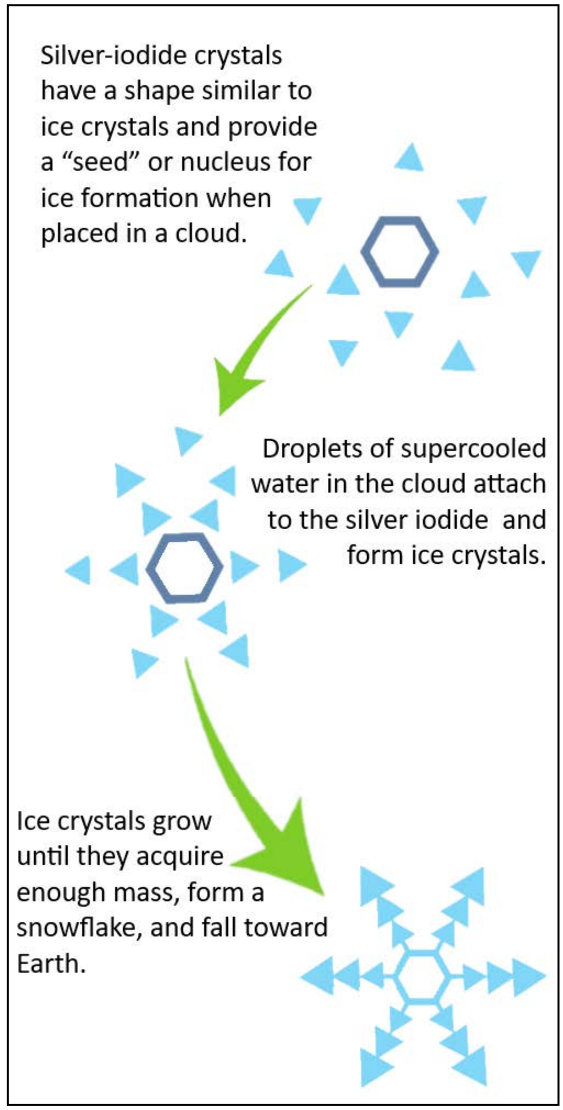
Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.

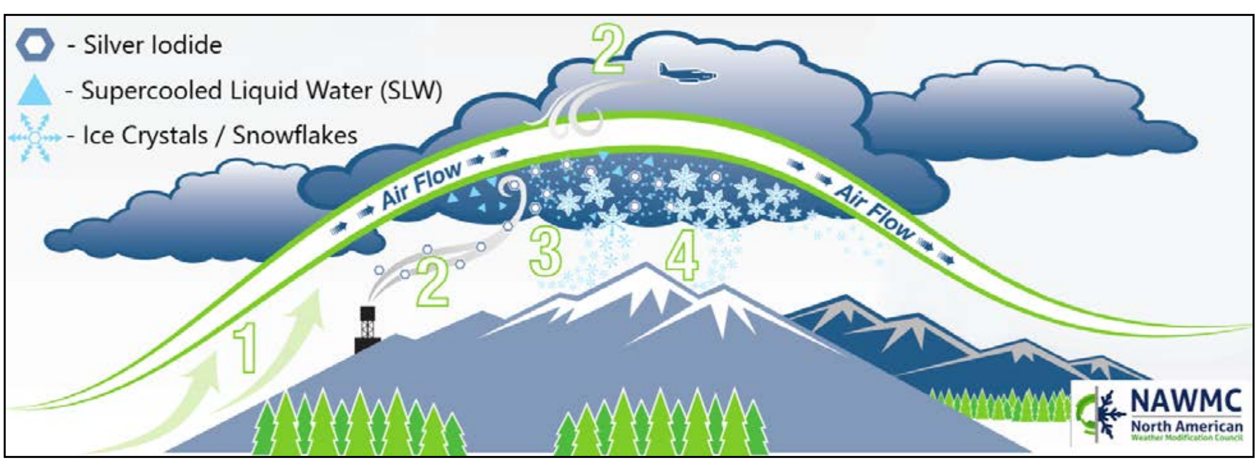
Safety

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

Effectiveness

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





CLIMATOLOGICAL UPDATE

The 2022-2023 water was defined by an exceptionally productive winter season. The winter brought essential relief to many of Utah's streams, rivers, reservoirs and lakes. As we consider the current state of Utah's watersheds, it is important that we consider the health in the context of long-term climatological trends.

Over the past 100 years the American Southwest has experienced a significant warming trend, as evidenced by the latest atlas 30 (see figure 1). Since the early 2000's Utah has been in what many have classified as a long-term drought. When compared to the previous 100 years, however, we find that the precipitation between 1991 and 2020 was actually in line with the prior 100-year average rainfall. This means that what we have classify as a "drought," is seemingly the norm not the exception (see Figure 2).

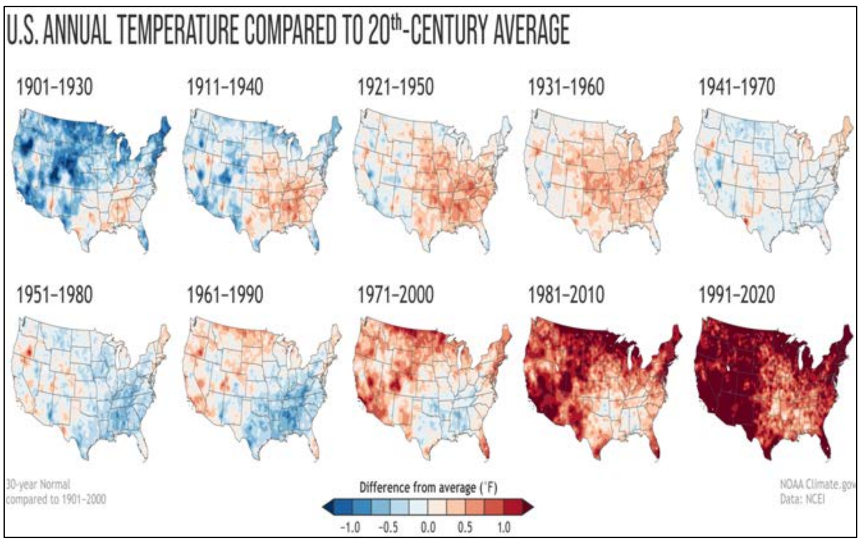


Figure 1 **U.S. Annual Temperature compared to 20th-Century Average**

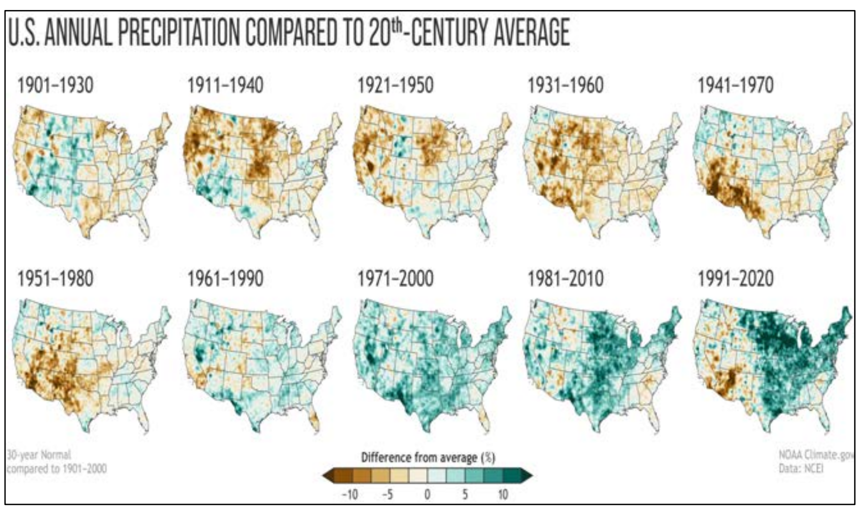


Figure 2 **U.S. Annual Precipitation compared to 20th-Century Average**

Snowpack in parts of the Six Creeks watershed reached record highs for numerous periods throughout the winter months. Nevertheless, the Great Salt Lake is still below its 20-year average and currently (as of June 1 2023) rests at 4,193.8 feet. At this level ecosystems and industries are still strained or endangered (see Figure 3). Though supporting the Great Salt Lake is not the primary objective of this program, augmenting runoff into the Great Salt Lake through cloud seeding has a meaningful impact on Salt Lake City's economy and air quality.

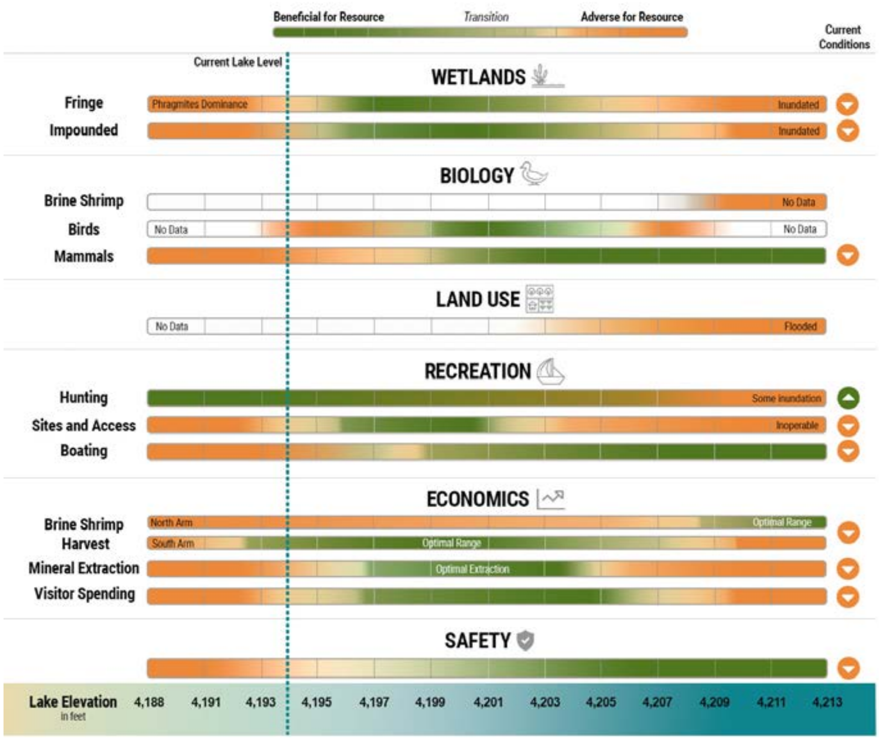


Figure 3. **Great Salt Lake Elevation and threat levels by industry/ecosystem.**

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EXECUTIVE SUMMARY

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, 2022 and was contracted through April 15, 2023. However, abnormally high snowpack this season (with some SNOTEL sites being above their entire recorded record) resulted in an early end to the seeding program, based on discussion of flooding potential between NAWC and the program sponsors including the Division of Water Resources. The program was suspended in February, with the last seeded event occurring on February 8. A total of 16 storm events were seeded during the 2022-2023 season, using a network of eight ground-based silver iodide generators, although a couple of the early season events were targeted primarily to the Snowbird resort program which is within the larger Six Creeks watershed. In total there were three seeded events in November, six in December, five in January, and two in February. A total of 839.25 cumulative hours of seeding generator operations were conducted specifically for the Six Creeks program during the season.

Snowpack and precipitation were again far above normal in the Six Creeks project area during the 2022-2023 winter season. It is worth noting there was a La Niña pattern in place similar to the previous two (dry) winter seasons. As of April 15, 2023, sites in the Six Creeks target area reported snowpack water equivalent values ranging from roughly 180% of 300% or greater of the median values for that date, with an overall basin value well over 200% of the average (median). Significant avalanche/mudslide and snowmelt flooding concerns continued to increase through the end of the season, resulting in the program remaining suspended through the end of the season.

Target/control evaluations have been 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 period totals. For this report, consistent with last season's analysis, the December – March regressions were applied to the current season. 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 (December – March precipitation, November – April precipitation, and April 1 SWE), both linear and multiple linear regression equations were developed.

Results of the precipitation regression analyses for Water Year 2023 were quite variable, with the precipitation evaluations (December – March, linear and multiple linear) yielding observed/predicted ratios of 1.00 and 1.04, respectively. In contrast, the snowpack evaluations (April 1 SWE, linear and multiple linear) single-season yielded ratios of 0.76 and 0.75, respectively, for this season. This result is not surprising given that cloud seeding was suspended in early February, and nearly half of the snowpack in the Six Creeks watershed accumulated AFTER the suspension date. **The 2023 single-season results were excluded from the longer-term results for a variety of reasons as discussed in Section 6.4. The four-season mean of evaluation results from 2019-2022 mean yielded ratios of 1.01 and 1.03 (precipitation linear and multiple linear), and 1.09 and 1.10 (snowpack linear and multiple linear).** In general, an 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, and thus the evaluation results are not particularly reliable or stable at this point. As the program continues to operate in the future, a more statistically significant increase value will be possible to determine.

Recommendations

Cloud seeding is intended to be a proactive not reactive long-term solution to support watershed health and sustainability. It's important to make hay while the sun shines, and rain when there's clouds in the sky. In considering the cities approach to cloud seeding this coming season, NAWC would encourage the city to remember how fragile our resources have become and how quickly the conditions of Utah's many watersheds can change.

NAWC has long advocated for a remote generator to be placed on the ridge above the state capital. NAWC continues to advocate for this addition to the generator network. NAWC believes he state will support the cost of the equipment itself, but NAWC would appreciate the support of the city in securing a location to place the equipment and perhaps in supporting some of the small monthly operational expenses.

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. 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. 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 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 2022-2023 season.

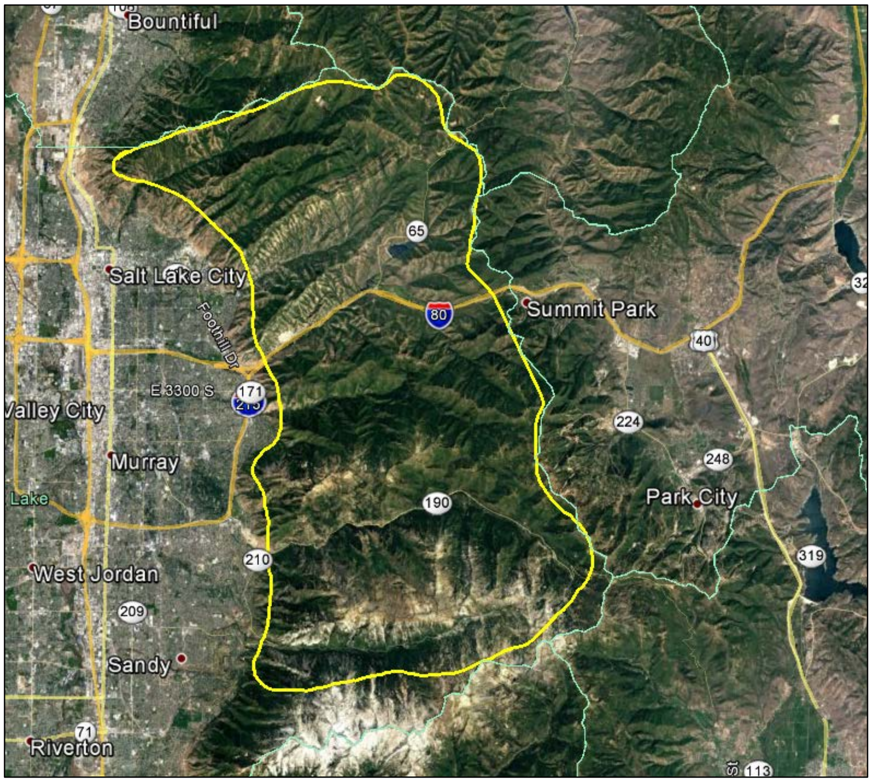

Figure 1.1 **Six Creeks Target Area**

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

3.1. Background

Operational procedures during the 2021-2022 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.

3.2. 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.

3.3. Equipment and Project Set-Up

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. One site was relocated this past season due to logistical issues at the previous site in Little Cottonwood Canyon. The current site should be similarly effective in targeting seeding material to the Wasatch Range in general, and perhaps more effective in getting seeding material quickly to a higher elevation.

The cloud seeding equipment at each site includes a cloud seeding nuclei generator and a propane gas supply tank. Figure 3.2 shows 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.

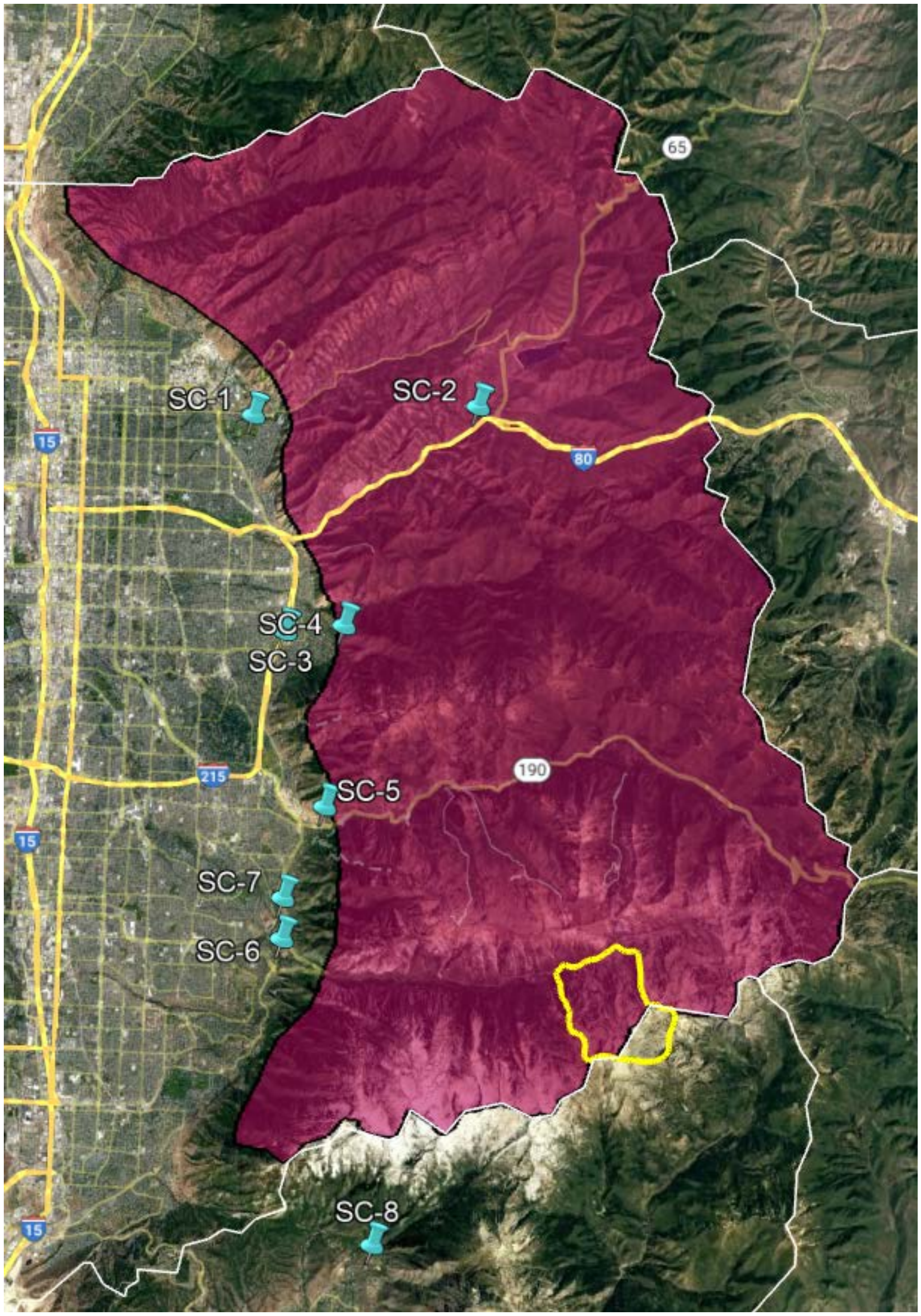

Figure 3.1 **Target Area (pink shading) and seeding sites (blue pins)**

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 – 4.4 show examples of some of the available weather information that is used in this decision-making process for operational cloud seeding programs.

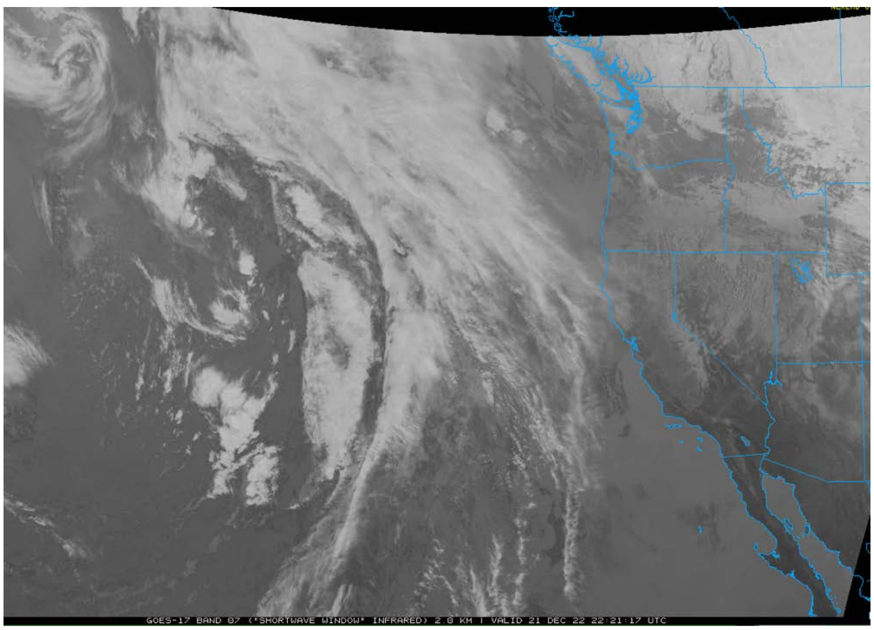

Figure 4.1 **Infrared satellite image on December 21, 2022 showing a large system in the eastern Pacific and a weak system over Utah**

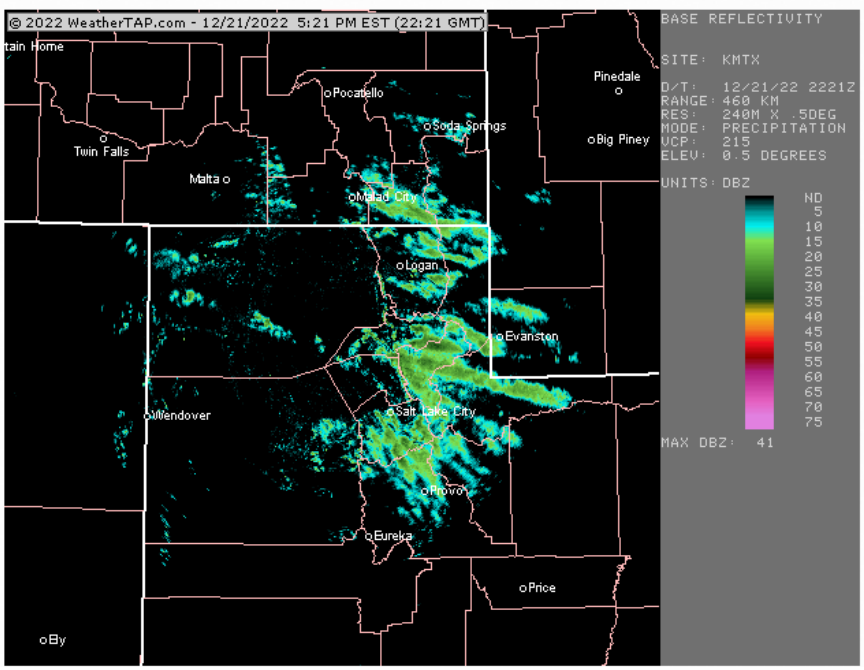

Figure 4.2 Radar reflectivity over northern Utah on December 21, 2022

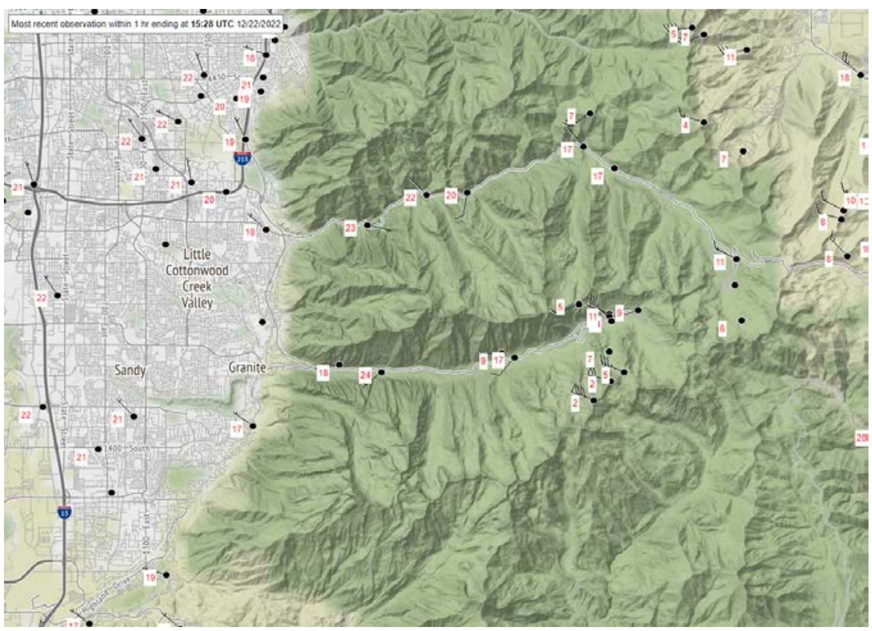

Figure 4.3 Map of surface observations in the Six Creeks area on December 22, 2022

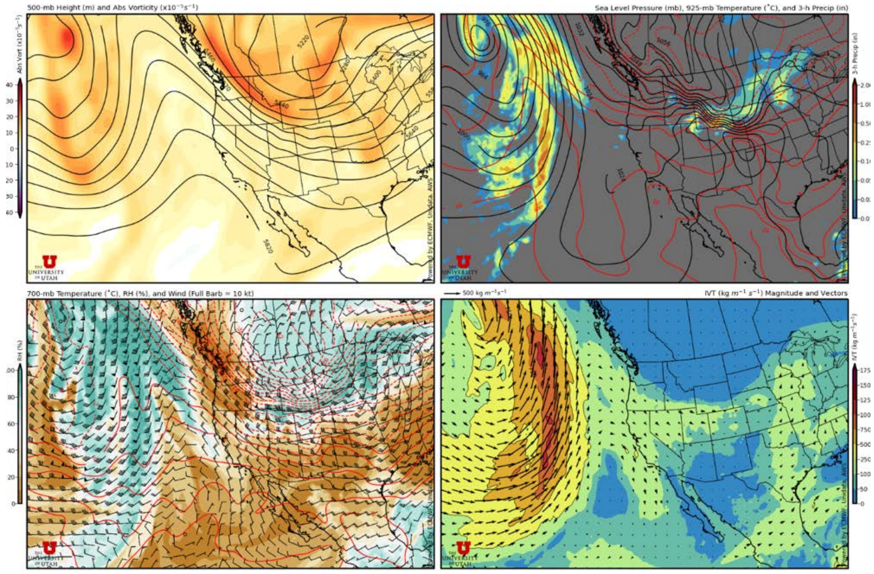

Figure 4.4 **Example of GFS (Global Forecast System) model data on December 21, 2022. Forecast model data is widely used by program meteorologists in the analysis and forecast of conditions favorable to seeding operations.**

5. OPERATIONS

This season's cloud seeding program for Six Creeks target area became active on in November 2022 and was contracted through April 15, 2023. Due to exceptionally heavy snowfall this season, the program ended in February with the final seeding operations in a storm on February 8. A total of 16 storm events were seeded during all or portions of 29 days, although in a couple of these storms seeding was only targeted to the Snowbird resort program within the larger Six Creeks watershed. In total there were three seeded events in November, six in December, five in January, and two in February. A total of 839.25 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 a and b provide the hours of generator operations by generator site location.

Table 5-1
Storm Dates and Generator Usage, 2022-2023 Winter Season

Storm Number	Storm Period	Number of CNGs Operated	Generator Hours
1	November 2	1	13
2	November 9-10	Snowbird only	
3	November 28-29	5	82
4	December 1-2	Snowbird only	
5	December 11-14	7	173
6	December 15	3	12
7	December 21-22	4	64.5
8	December 27-28	5	105
9	December 30-31	6	22
10	January 5-6	5	39
11	January 10-11	8	106.75
12	January 15	5	24
13	January 17-18	6	99.5
14	January 27-28	4	65
15	February 6	4	26
16	February 8	4	7.5
Total	---	---	839.25

Table 5-2a
Generator Hours for 2022-23, Storms 1-10

Storm	1	2	3	4	5	6	7	8	9	10
Date	Nov 2	Nov 9-10	Nov 28-29	Dec 1-2	Dec 11-14	Dec 15	Dec 21-22	Dec 27-28	Dec 30-31	Jan 5-6
SITE										
Baskin Reservoir			22		24	3.5	21.5		3.75	
Mountain Dell Treatment			19		45	4.5		10.75		
4500 S Pump House			17		24		21.5	19	3.25	6
White Reservoir	13		20		24	4	21.5	17	3.75	6
Big Cottonwood Treatment					34			33.25	4.25	6
Little Cottonwood Canyon								25	3	7
Sandy Metro										
Alpine			4		22				4	14
Storm Total	**13**	*	**82**	*	**173**	**12**	**64.5**	**105**	**22**	**39**

*** Seeding counted for Snowbird only, not for Six Creeks program**

Table 5-2b
Generator Hours for 2022-23, Storms 11-16

Storm	11	12	13	14	15	16
Date	**Jan 10-11**	**Jan 15**	**Jan 17-18**	**Jan 27-28**	**Feb 6**	**Feb 8**
SITE						
Baskin Reservoir	6	5	17	17.5	6	2.25
Mountain Dell Treatment	5.75		16.75		7	
4500 S Pump House	18.75	5.25	17			
White Reservoir	18.5	5.5	17	17.5	6	2.75
Big Cottonwood Treatment	19	4.75	16.75	15.5	7	2
Little Cottonwood Canyon	16.75		15	14.5		0.5
Sandy Metro	9	3.5				
Alpine	13					
Storm Total	**106.75**	**24**	**99.5**	**65**	**26**	**7.5**

Snowfall for the 2022-2023 winter season was far above normal, exceeding 200% of the seasonal average (median) values at most sites. This high snowpack resulted in early suspension of the seeding program during February. Data for each SNOTEL site as of April 15 is provided in Table 5-3. These values roughly represent the maximum values at most of these sites this season.

Table 5-3
Snowpack and Precipitation Data from SNOTEL sites – April 15, 2023

Measurement Site	Snow Water Equivalent (in)			Water Year Precipitation (in)		
	4-15-23	Median	%	4-15-23	Median	%
Louis Meadow	38.9	6.5	598%	42.8	22.5	190%
Lookout Peak	52.9	25.8	205%	52.7	30.8	171%
Parleys Summit	45.8	na	na	40.5	na	na
Mill-D North	56.7	22.2	255%	50.3	25.8	195%
Brighton	41.0	22.2	185%	45.0	26.2	172%
Snowbird	70.6	38.8	182%	58.7	35.5	165%
Basin Index %			232%			170%

Figures 5.1 to 5.3 show plots of data from three SNOTEL sites located in the target area during the 2022-2023 winter season, ending in mid to late 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.

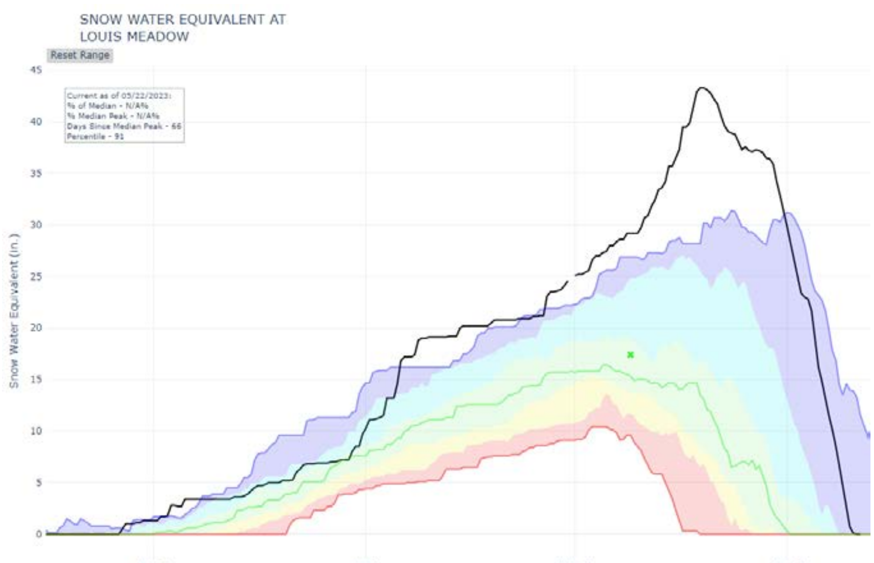

Figure 5.1. **NRCS SNOTEL snow and precipitation plot for Louis Meadow. Historical max/min values shown as purple and red lines; median as green; current season as black.**

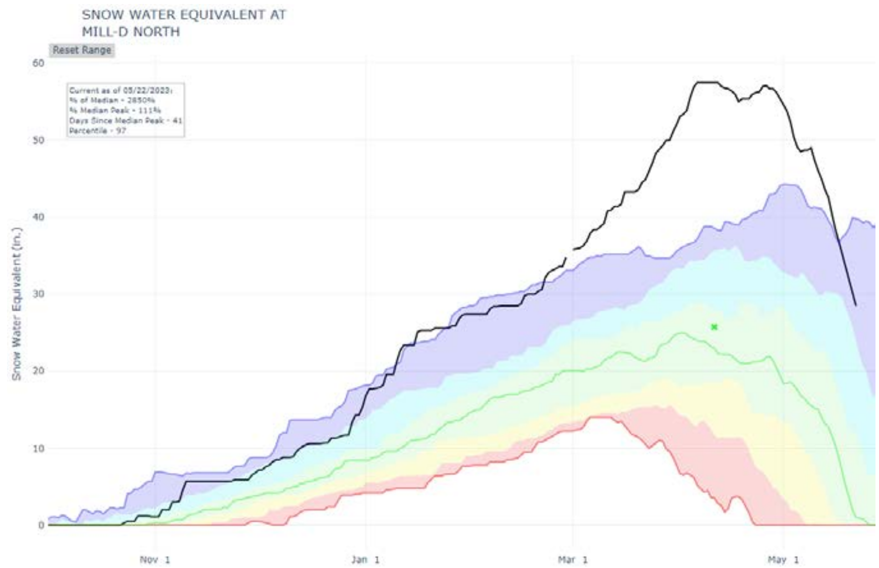

Figure 5.2. **NRCS SNOTEL snow and precipitation plot for Mill D – North. Historical max/min values shown as purple and red lines; median as green; current season as black.**

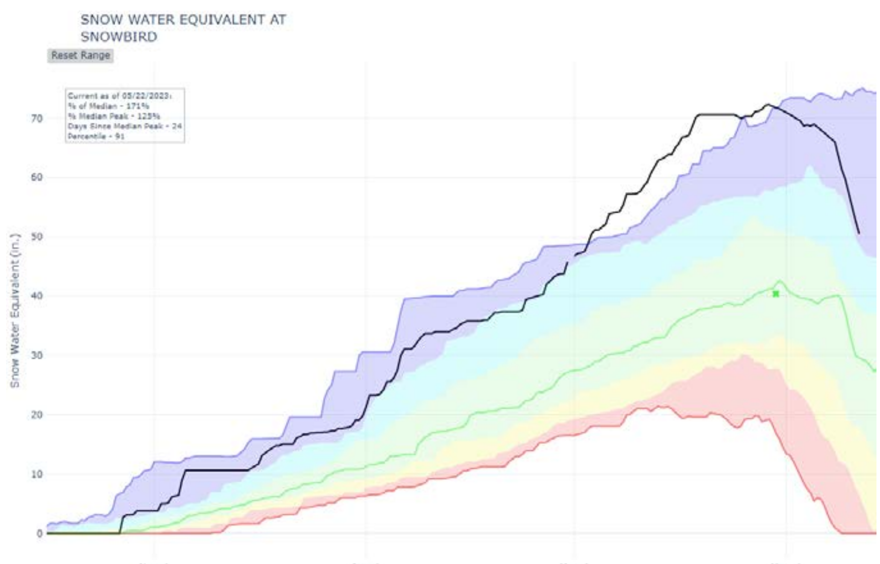

Figure 5.3. **NRCS SNOTEL snow and precipitation plot for Snowbird. Historical max/min values shown as purple and red lines; median as green; current season as black.**

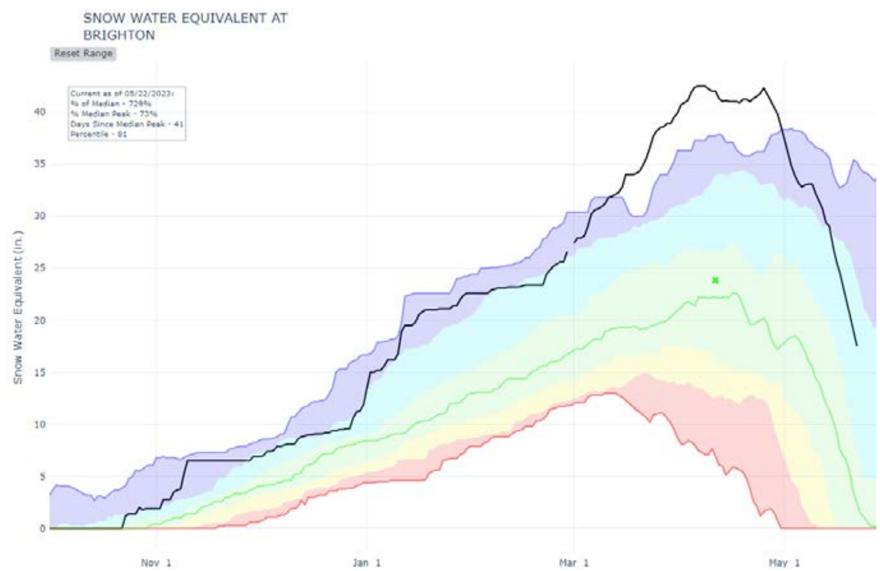

Figure 5.4 **NRCS SNOTEL snow and precipitation plot for Brighton. Historical max/min values shown as purple and red lines; median as green; current season as black.**

5.1. Operational Procedures

In operational practice, approaching storms were 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 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.

5.2. 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 2022

Precipitation was quite variable in November, highly favoring west-central portions of Utah and generally above normal in the Six Creeks watershed. There were two seeded storm events for the Six Creeks watershed in November, and another targeting the Snowbird resort only.

A frontal system on November 2 stalled in the Salt Lake City area for a time with a period of moderate to heavy snowfall. Despite potential low-level stability challenges to material dispersion, a few sites were operated for southern portions of the watershed and mainly for the Snowbird resort area during the day on November 2. By late in the day, snow showers tapered off and seeding ended. The 700 mb temperature dropped to around -10°C following the frontal passage making conditions sufficiently cold for seeding. Precipitation totals reached close to an inch of water equivalent in portions of the target area during this event.

A major snowfall event on November 8-9 brought 2 feet or more of snowfall with about 2-3" of water equivalent to much of the Six Creeks area. Winds were mostly unfavorable for seeding in this event, although the southernmost site at Alpine was used to target mainly the Snowbird area and the seeding hours were designated to that program.

After a period of mostly dry weather and some valley temperature inversions, another system affected the area late in November. A cold front arrived around midday on the 28th, with graupel mixing into the snow initially which indicated some pockets of decent liquid water content. Snowfall tapered off to showers but continued overnight with some lake effect snow in northwesterly flow across the Six Creeks area. Temperatures became quite cold by the morning of November 29, down to about -15°C at the 700 mb level. By late morning on the 29th, snow tapered off and seeding ended. All seeding sites were utilized in this event, with many of these designated for the Six Creeks program and some specifically for Snowbird. Precipitation totals ranged from about a half inch to just over an inch of water content within the Six Creeks watersheds.

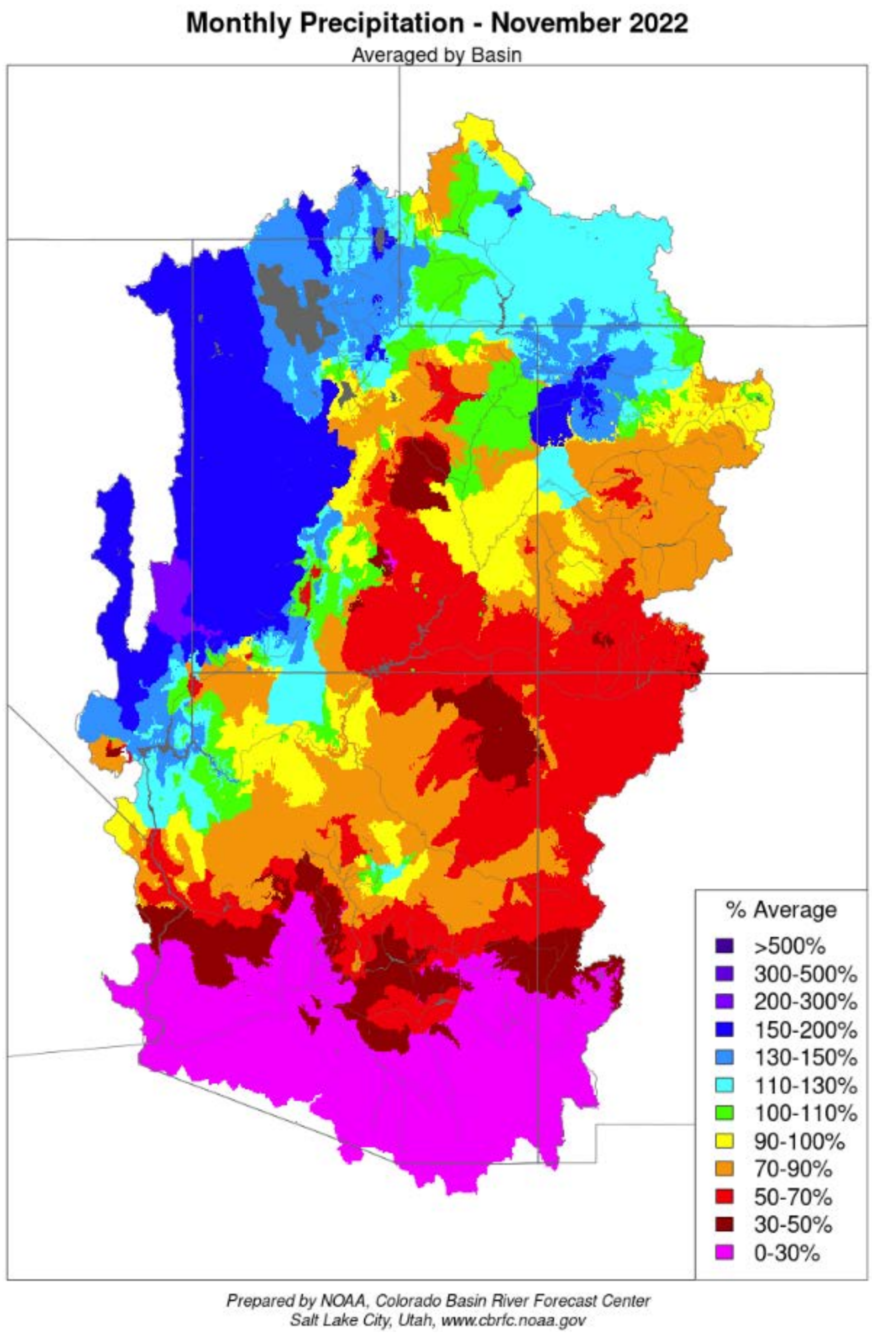

Figure 5.5 **November 2022 precipitation percent of normal**

December 2022

December brought several significant storm events and well above normal snowfall for the month. Figure 5.6 shows monthly precipitation as a percent of the median values. There were six seeded storm events in December, although the first of these on December 1-2 had seeding designated only for the Snowbird area.

A cold frontal passage on the night of December 1-2 appeared generally lacking in cloud liquid water, with only a narrow zone of liquid water forecast during the frontal passage overnight. One site was targeted to the Snowbird area overnight where conditions appeared most favorable, but no other seeding was conducted. The forecast verified with only a few inches of low-density snow accumulation overnight, suggesting that the natural ice process was strongly dominant in this event and not very conducive to seeding.

After a period of dry weather, a major storm affected the area during the December 11-14 period. A large trough with a core near the California coast brought a band of precipitation into Utah late on December 11. Seeding was initiated from a few sites; however, more seeding sites were activated on December 12 with a predominant westerly wind, lower cloud bases, and colder temperatures. Cooling temperatures aloft resulted in an increase in snow shower and snow squall activity later in the day, and this activity appeared quite favorable for seeding. The following night (December 12-13) featured continued light snow showers which were likely lake-enhanced, and seeding continued at sites favorable to northwesterly flow. The 700 mb temperature dropped to around -12°C, still favorable for areas of liquid water. There was a break in the seeding on December 13 with only light northerly winds and apparent lack of cloud liquid water. There was a secondary period of seeding late on December 13 and overnight as winds became more northwesterly again and there was some potential for lake effect moisture as well as decent orographics. By early on the 14th, conditions appeared poor and seeding activity was terminated. This long storm period in general brought between about 1.5 – 2.5” of water content to the Six Creeks area, and periods of good seeding opportunity.

A weak system, generally lacking in moisture, traversed the area from north to south on December 15. There was a period of decent vertical cloud development over the Wasatch Range from midday into the afternoon hours, and seeding was conducted at several sites for a few hours despite limited snow shower activity. Seeding ended by late afternoon, and precipitation totals were light with 0.1 to 0.3” of water content.

A deep, cold arctic trough to the north of the area drove a strong westerly wind pattern across northern Utah on December 21-22. While lower elevation winds were fairly light, winds near and above the 700 mb level became very strong in some areas with Snowbird recording record high wind gusts to 130 mph on the night of December 21-22. There were some periods of good orographic snowfall, and seeding was conducted at some sites on December 21 and overnight. The strong winds made targeting somewhat of a challenge, however, and seeding operations ended by early on December 22. Precipitation amounts were mostly on the light side but amounted to locally a half inch or more of water content in higher portions of the Wasatch Range. Following this event, an arctic air mass arrived at lower levels of the atmosphere and resulted in mostly dry and very cold weather for a few days.

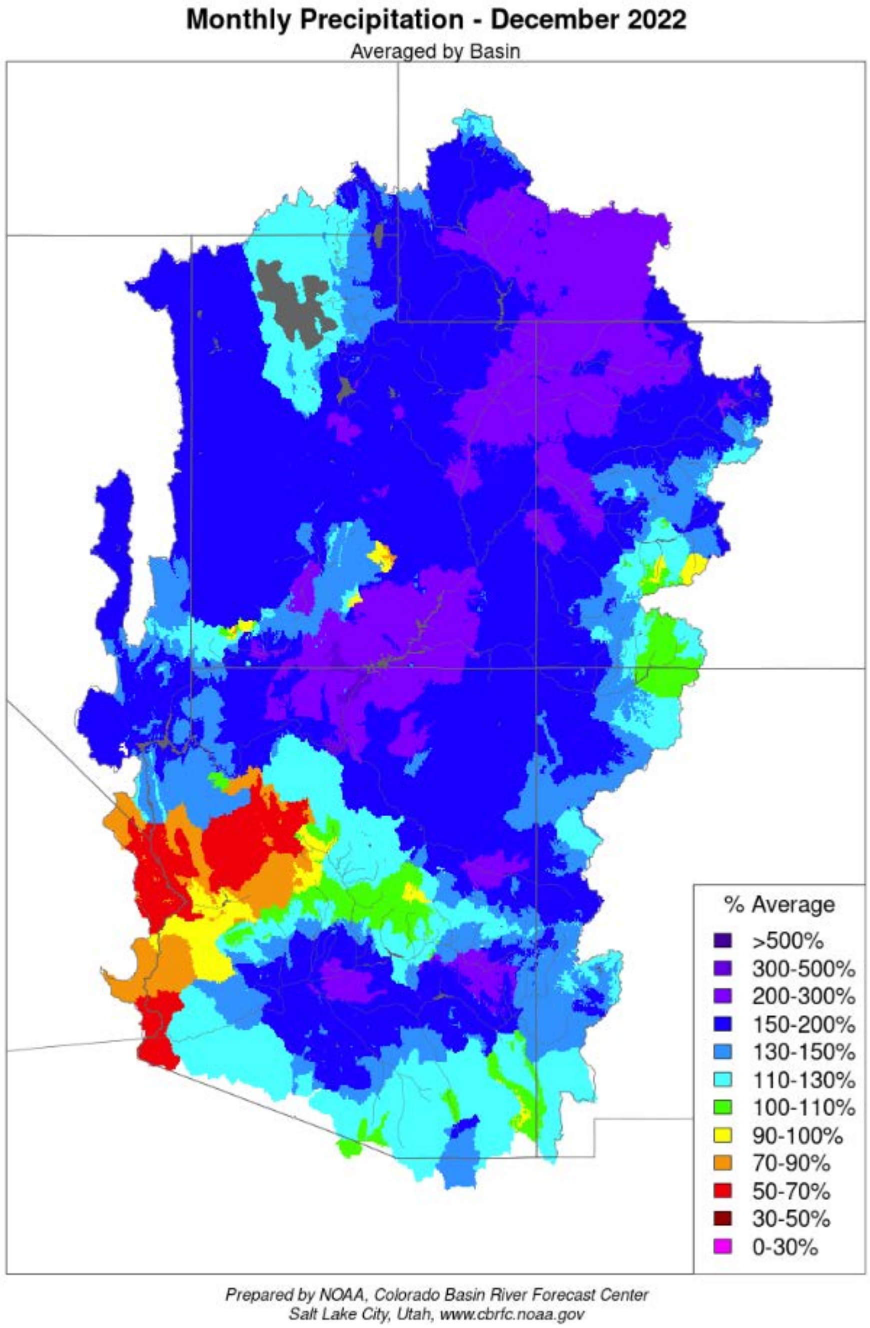

Figure 5.6 December 2022 precipitation, percent of average

A large and vigorous trough over the Pacific Northwest on December 27 brought a large band of subtropical moisture across Utah, with mild temperatures in southwesterly flow. The freezing level was initially near 700 mb and warm temperatures made conditions unfavorable for seeding at first, although temperatures cooled overnight (Dec 27-28) and a band of somewhat convective precipitation crossed the area with the arrival of the core area of the trough. Seeding began during this period at several sites. As the core of the trough crossed the area on December 28, snow showers were accompanied by visual observations of cloud types that appeared very good for seeding operations. The temperature cooled to -10° to -12°C at the 700 mb level which was favorable, and seeding operations continued through the day on the 28th. Conditions became less favorable after sunset although one site remained active overnight with a fairly solid cloud deck over the Wasatch and areas of very light snowfall. Precipitation totals with this storm event ranged from 1.5 – 2.5” of water content in most of the Six Creeks area, although much of this occurred in the warm portion of the storm before seeding operations began.

A large area of warm advection precipitation on December 30 was followed by some gradual cooling and better cloud types for seeding operations on the 31st. Although seeding was conducted briefly in southerly flow on the 30th, there was a period on December 31 with somewhat more favorable conditions and winds. However, these seeding periods were limited. Avalanche conditions were also becoming quite high in the Cottonwood Canyons and these areas were generally avoided for operations. Although seeding opportunity was limited during this period, there were impressive snowfall totals in the Wasatch with water content of over 2” to locally as high as 4” during a 2+ day time period.

January 2023

The weather pattern remained very wet and stormy in January, with well above normal snowfall in the target area. Regional precipitation patterns as a percentage of normal in January are shown in Figure 5.7, with over twice the normal January precipitation across most of Utah. There were five seeded storm periods in January.

A large storm system moved from California into the Great Basin on January 5. The 700 mb temperature warmed to about -5°C in southwesterly flow, and light precipitation began in the afternoon and evening hours. While winds shifted to a more westerly direction at the 700 mb level overnight, they remained south-southeast at lower levels. Seeding was initiated at the Alpine site on the evening of the 5th, and transitioned to sites in the Salt Lake Valley on the morning of January 6. Valley winds became light and variable during the day on January 6, with west to northwest winds aloft and a 700 mb temperature near -7°C. Seeding conditions appeared fair although with multiple cloud decks it was hard to pinpoint the origin of much of the snowfall aloft. Orographic snowfall over the Wasatch was noted but decreased during the afternoon hours, at which point seeding was discontinued. Precipitation totals with the January 5-6 event amounted to between 1.0 – 1.5” of water content in most of the Six Creeks target area.

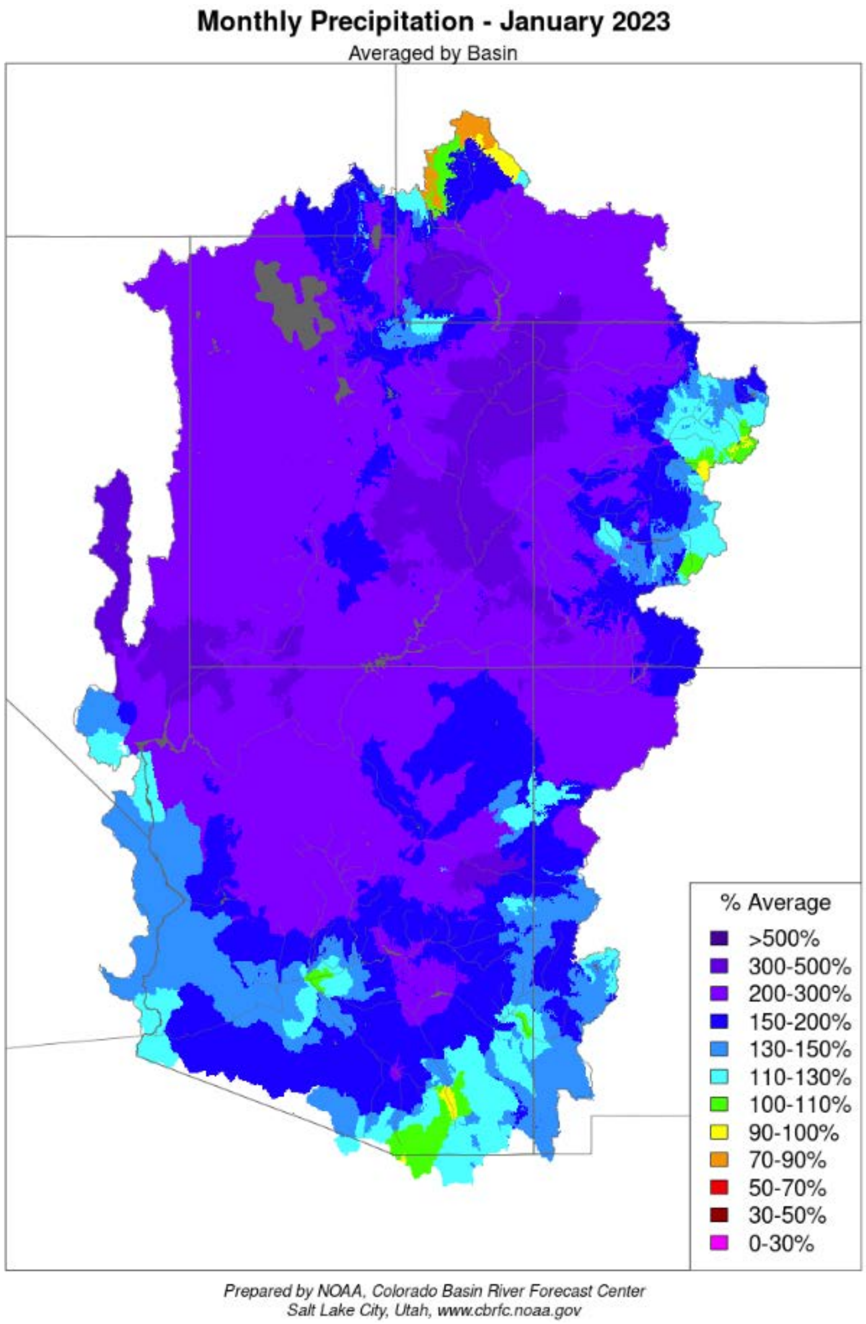

Figure 5.7 **January 2023 precipitation, percent of average**

A large subtropical moisture plume reached Utah on January 9 and lingered into early on the 10th, with temperatures too warm for seeding operations during the initial precipitation period, although seeding began at a couple of sites on the morning of the 10th. A strong cold front arrived later on January 10, accompanied by some convective activity, at which point seeding operations were increased to include most sites. Winds shifted to northwesterly on the night of January 10-11 with the 700 mb temperature dropping to around -10°C. Light snowfall and a fairly thick lower cloud deck based near 8,000 to 10,000 feet remained through much of January 11 and seeding continued into the early afternoon hours. After about 1400 MST, snow showers and seeding operations ended. Precipitation totals for just the seeded portion of this event amounted to 1-2” of water content, with the overall total for the event having much higher totals at some sites.

A trough moving onshore on January 14 began to spread light precipitation over Utah on the night of the 14th-15th. Seeding conditions were initially poor due to marginal temperature and wind patterns as well as cloud types. By the morning of January 15, a mid to upper-level circulation center had developed over northern Utah with valley rain and mountain snow, as well as cold cloud tops and precipitation initiating fairly high in the atmosphere. By midday there was a shift to northwesterly winds at lower levels and a lower cloud deck developed along the Wasatch Range. Seeding operations were initiated at this point with 700 mb temperature near -7°C. There was a mix of valley rain, snow and drizzle during the afternoon hours resulting from moist upslope flow, and seeding continued until around sunset. Showers largely ended after sunset with a transition to light down sloping winds at the surface. Precipitation totals with this event were generally over a half inch of water content in the target area.

A trough moving across the region became a compact upper low center as it moved across Utah on January 16-17. On the 17th this feature began to produce light precipitation and some lower clouds in the Six Creeks area, with winds gradually becoming northwesterly in the lower levels by afternoon. The main low center moved into western Colorado later on the 17th. For the Six Creeks program, seeding began during the afternoon of January 17 when lower-level winds became northwesterly, although there were some northeasterly winds above 7,000 to 8,000 feet elevation making targeting tricky. This situation continued on the night of January 17-18 with some seeding overnight, ending early on the 18th with clearing skies. Precipitation amounts with this system were pretty light in the Six Creeks area, generally 0.2 – 0.3” of water content.

A trough developing north of the area on January 27 resulted in gradually improving conditions for seeding as winds became light west to northwest at lower levels by afternoon. An initial higher cloud deck gave way to more orographic clouds with modest amounts of cloud liquid water indicated over the Wasatch Range. The 700 mb temperature was near -8°C, favorable for operations, and seeding was gradually initiated during the afternoon to early evening hours for west to northwest winds. Some snow showers continued into the morning of January 28 with seeding ending late morning on the 28th as precipitation slowly tapered off. The 700 mb temperature had cooled to -12°C by the morning of the 28th. Precipitation totals were generally near a half inch of water content.

February 2023

Precipitation totals in February were much more variable than in January, although for the Six Creeks area they were still well above the monthly average. Figure 5.8 shows February totals as a percent of the median across the region. After a couple seeded storm events in early February, concerns about snowmelt flooding continued to increase as some SNOTEL sites in the target area approached or exceeded their recorded climatological maxima in snow water content. Based on discussions between NAWC and program sponsors / Division of Water Resources, seeding operations were suspended after the February 8 seeded event.

A frontal system on February 5-6 brought some snowfall beginning on the 5th, although lower levels were too stable for seeding operations initially due to pre-existing valley inversions. A large trough was centered over the Four Corners region by February 6 with snow showers in northwesterly flow across northern Utah, and colder temperature near -10°C at 700 mb resulted in good mixing. Seeding was conducted from the morning through early afternoon hours on February 6 for sites favorable to northwesterly flow. By mid-afternoon winds became almost due northerly with just thin overcast clouds, and seeding operations were terminated. Precipitation totals during the seeded portion of this event were generally around a quarter to half inch of water content in the target area.

A cold trough was centered over the northern Rockies region with a cold front brushing northern Utah on February 8. There was a brief period of snow showers that developed during the mid to late afternoon, with clouds based near the 700 mb level where temperatures were near -8°C. Seeding was conducted from several sites during the late afternoon and early evening, with precipitation amounts of only around 0.1” of water content at most SNOTEL sites. This was the final seeding event of the season, as the decision was reached to suspend the program after this event. This suspension continued for the remainder of the contracted season, with the month of March again bringing exceptional (over twice the monthly average) snowfall to the area as seen in Figure 5.9. Snowfall during April was concentrated early in the month and was quite variable locally, although generally close to average for the month as a whole. As of the middle of April, snowpack remained over twice the seasonal median over the area as a whole and remained above all previous records at some SNOTEL sites.

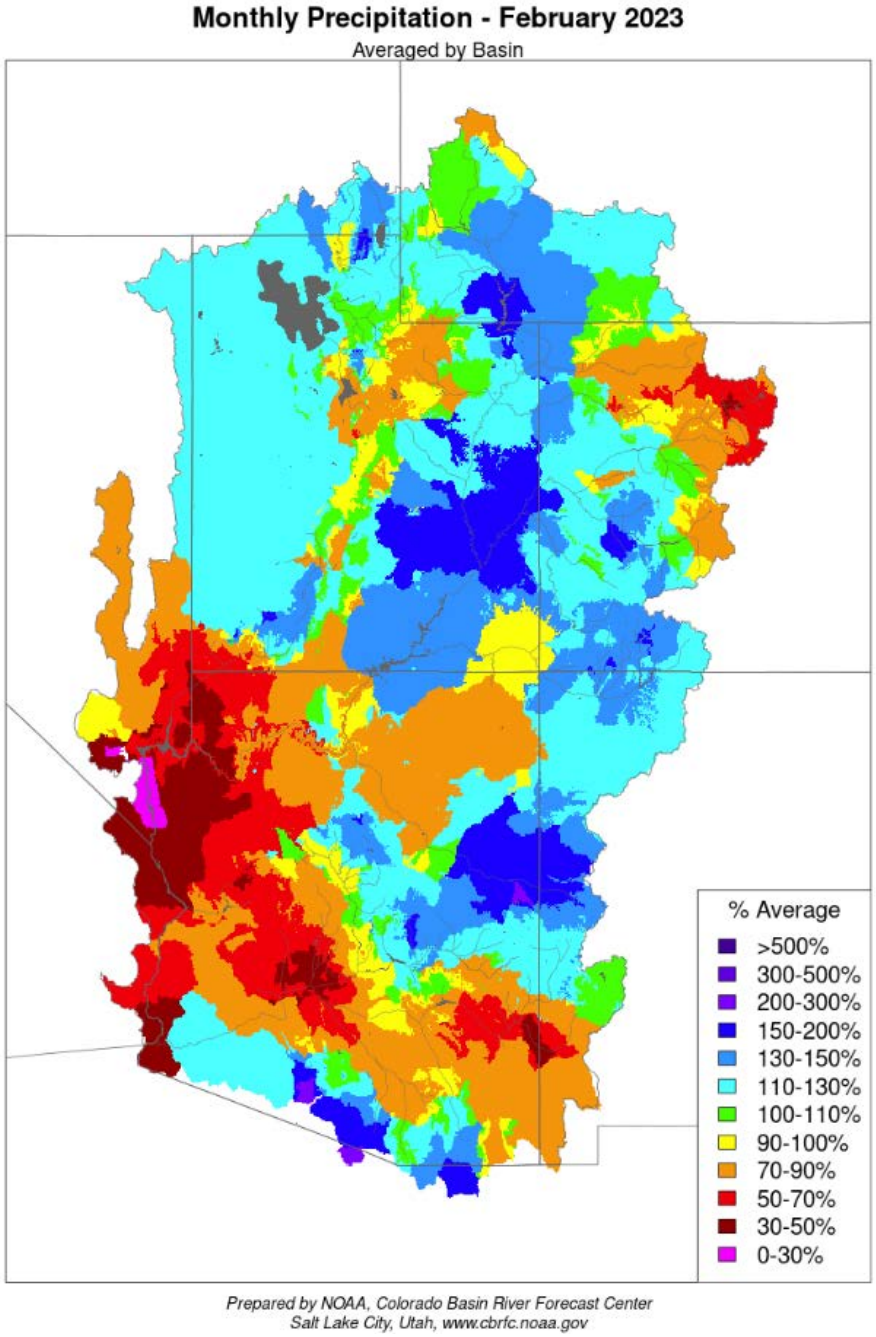

Figure 5.8 **February 2023 precipitation, percent of average**

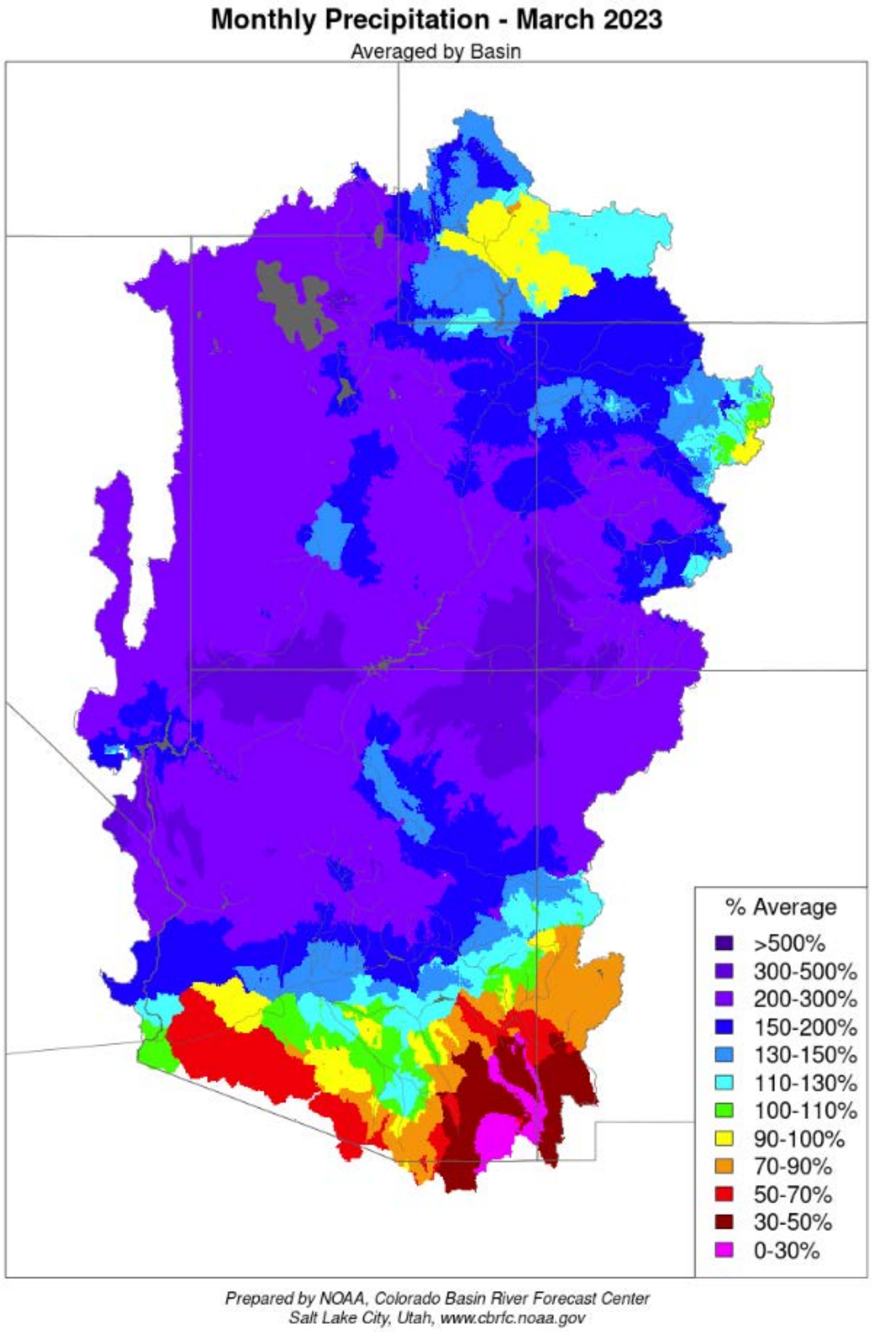

Figure 5.9 **March 2023 precipitation, percent of average**

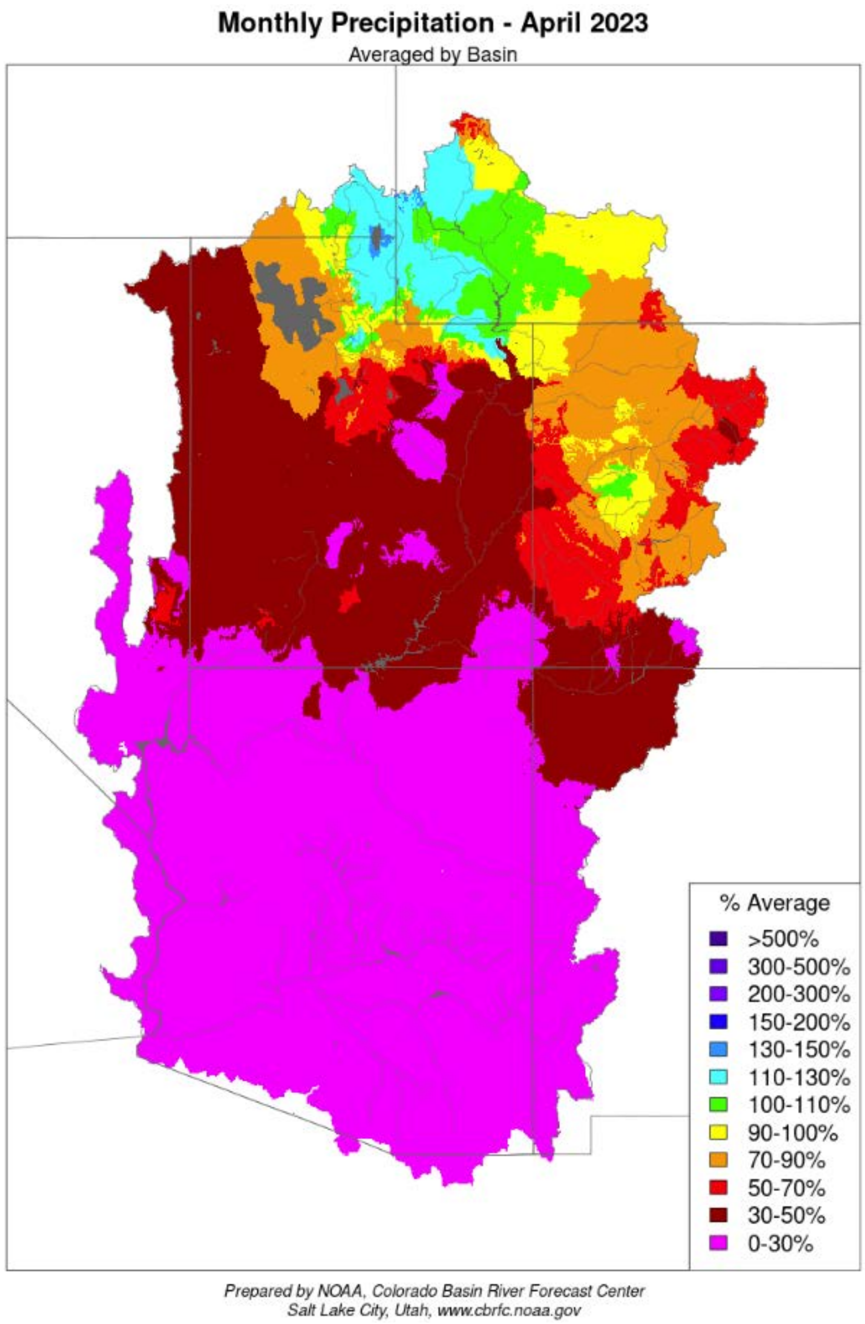

Figure 5.10 April 2023 precipitation, percent of average

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:

$$SE = (Y_O – Y_C) / (Y_C \times 100)$$

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 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. Results for the Current Season and Composite of Seeded Seasons

Evaluation results for the 2023 Water Year, as in many seasons, 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. 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 yielded observed/predicted ratios of 1.00 and 1.04 for this season linear and multiple linear equations, respectively, which is suggestive of a positive seeding effect. The snowpack evaluations yielded single-season ratios of 0.76 and 0.75 for the linear and multiple linear equations, respectively.

There are several 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.

For this season in particular, there were a number of unusual factors that resulted in a pretty obvious conclusion that analysis results for the 2023 water year would not be meaningful. First, **the seeding program ended very early this season due to high snowpack amounts, so a much lower percentage increase in precipitation or snow water content (due to the seeding program) would be expected. Almost half of the snow pack for this season accumulated after cloud seeding had been suspended.** Additionally, an abnormal weather pattern resulted in very high precipitation values which were high outliers (and at some sites completely outside the observed historical range) compared to the data in historical data regression period. Given the potential for non-linearity in the target/control regression relationships, outlier (very wet or dry) years are even less likely to produce a meaningful estimation of seeding effects than in a regular single season. Finally**,** a very high percentage of precipitation this season fell as snow instead of a more typical mix of rain and snow, even at the lower elevation SNOTEL sites. This particularly influenced the snowpack evaluations, as the geographical distribution of snow water content observed in the 2023 water year was very different than that observed in a more typical season. Given these factors, although the results for this season are shown in this section, it was considered unreasonable to include these in the long-term average for the program. Thus, the more meaningful numbers are based on previous (2019-2022) water years, although that remains a short seeded period as well in terms of confidence places in the target/control results.

In addition to the ratio of the observed to predicted values obtained from these equations, the predicted values can be subtracted from the corresponding observed values, to examine the difference in observed minus predicted values for the target area average. Whenever the observed/predicted ratio for a particular evaluation is less than 1.0, this difference will be negative, and when the ratio is greater than 1.0 the difference 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 obtained by the cloud seeding operations. As the the observed/predicted ratios, these numerical differences between observed and predicted values only become significant after a good number of seeded seasons and should not be considered significant for an individual season.

The second-to-bottom row in Table 6-3 summarizes the overall mean of the 2023 season's results, while the bottom row summarizes the overall mean for the period of 2019 through 2022 seasons (which excludes the current season as discussed above). There are some potential pitfalls with averaging the data in this way, but these mean values may aid in the interpretation of the mixed results from the different evaluation techniques. The overall four-season (e.g. 2019 through 2022) mean result is a ratio of 1.06, which could be taken to suggest a 6% increase in precipitation and/or SWE. This ratio is equivalent to roughly 1.20 inches of additional precipitation/SWE for the seasons.

A similar seeding program was conducted for this Six Creeks 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 1.01 (linear) and 1.02 (multiple linear). For April 1 SWE, results averaged 1.14 (linear) and 1.16 (multiple linear) for those earlier years.

Table 6-3
Evaluation Results Summary

Evaluation Type	Observed/Predicted Ratio	Observed – Predicted Difference (inches of precipitation or SWE)
Precipitation December-March Linear (single season only)	1.00	-0.01
Precipitation December - March Multiple Linear (single season only)	1.04	1.26
Snow April 1 Linear (single season only)	0.76	-10.20
Snow April 1 Multiple Linear (single season only)	0.75	-10.71
2023 Mean of Results	0.89	-4.92
2019-2022 Mean	1.06	1.20