Annual Cloud Seeding Report

Northern Utah Program

2022-2023 Winter Season

Prepared For:

Bear River Water Conservancy District

Box Elder County

Cache County

State of Utah, Division of Water Resources

Prepared By:

David Yorty

Jack Wiser

North American Weather Consultants, Inc.

8180 S. Highland Dr., Suite B-2

Sandy, Utah 84093

June 2023

Contents

EXECUTIVE SUMMARY

In past winter seasons beginning in 1989, cloud seeding has been conducted in portions of northern Utah. This includes the northern Wasatch Range of eastern Box Elder and Cache Counties above approximately 6,000 feet MSL, and separate ranges in northwestern Box Elder County above the same elevation. The Northern Utah Seeding Program utilizes over 30 ground-based, manually-operated Cloud Nuclei Generator (CNG) sites, containing a 2% silver iodide solution. The goal of the seeding program is to augment wintertime snowpack/precipitation over the seeded watersheds. Cost sharing for the seeding program is provided by the Utah Division of Water Resources.

Precipitation and snowfall were far above normal during the 2022-2023 winter season. A total of 2,360 CNG hours were conducted during 21 storm periods for the core program this season. Due to a continued increase in snowpack during March, the seeding program was suspended on March 24 with only a week left in the program contract. Although the SNOTEL sites designated as having suspension criteria (Franklin Basin, Tony Grove Lake, and Bug Lake) remained a little under the suspension thresholds, it was noted by NAWC that snowpack distribution by late March was somewhat atypical. The higher elevation sites normally used in runoff forecasts had very high SWE values (although not record high), while the lower sites, particularly near the 5,500 to 7,000 elevation range, had exceptional snowpack that exceeds all previous records in some areas. Given the increasing concerns about flooding and considering the additional major storm events still in the forecast, it was considered prudent to end the program at that point in the season.

Evaluations of the effectiveness of the cloud seeding program have been made for both the past winter season and for the combination of all seeded seasons. These evaluations utilize SNOTEL records collected by the Natural Resources Conservation Service (NRCS) at selected sites within and surrounding the seeded target areas. Analyses of the effects of seeding on target area precipitation and snow water content have been conducted for this seeding program, utilizing target/control comparison techniques. Evaluation of December – March precipitation data have suggested long-term average seasonal increases averaging 5-6% for the eastern Box Elder and Cache County portions of the program (where long-term precipitation records are available). This is equivalent to roughly an additional inch of precipitation seasonally. Similar regressions with April 1 snow water content data have suggested increases anywhere from 6-13%, implying increases between about 1.4-2.5 inches of water content. While it is not clear which of these results are the most accurate, they fall within the generally observed range of 5-15% increases for winter cloud seeding programs, and thus provide reasonable estimates. A 2012 study estimated a total (average) seasonal increase of approximately 56,000 acre-feet from the seeding program.

WEATHER MODIFICATION

The Science Behind Cloud Seeding

The Science

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

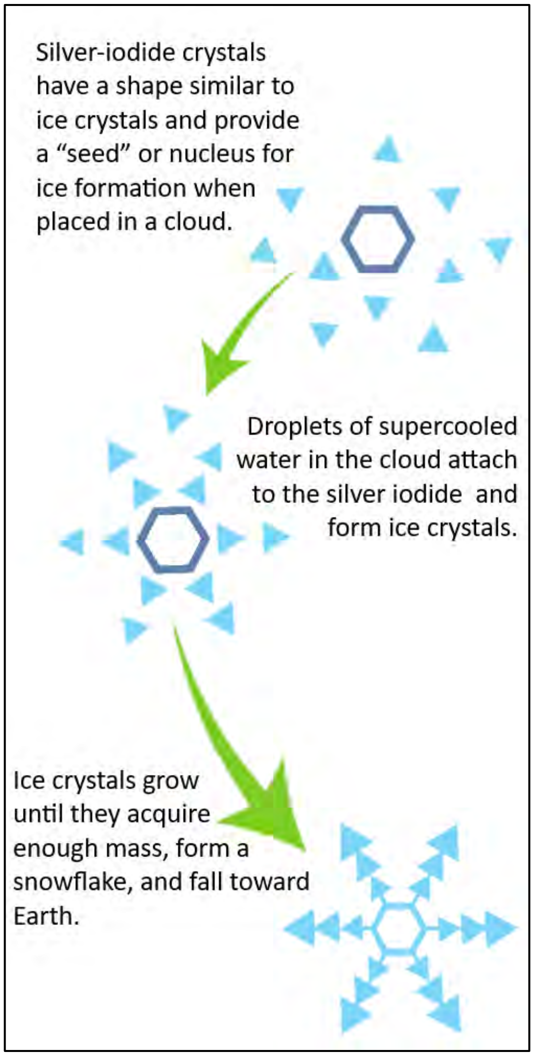
Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.

Safety

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

Effectiveness

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



Silver-iodide crystals have a shape similar to ice crystals and provide a "seed" or nucleus for ice formation when placed in a cloud.

Droplets of supercooled water in the cloud attach to the silver iodide and form ice crystals.

Ice crystals grow until they acquire enough mass, form a snowflake, and fall toward Earth.

STATE OF THE CLIMATE

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 determines 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 ranges from 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.

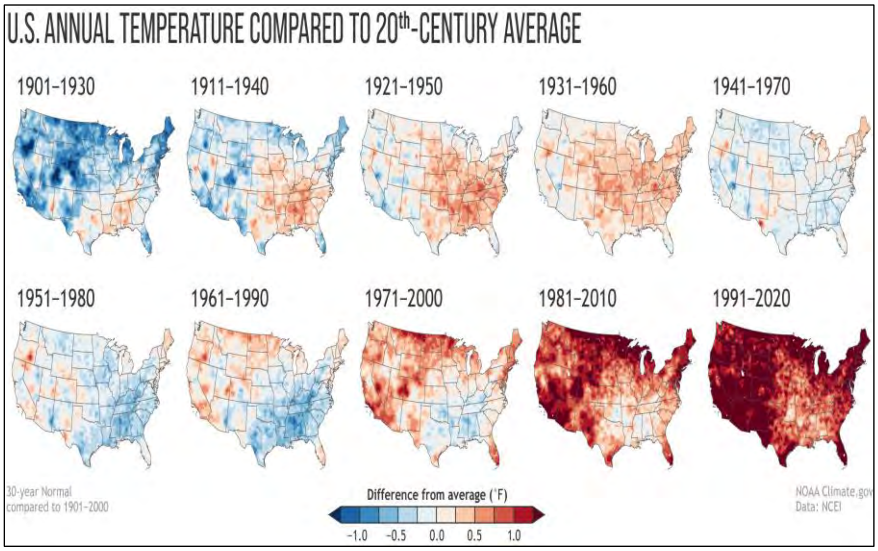


Figure 1 **U.S. Annual Temperature compared to 20th-Century Average**

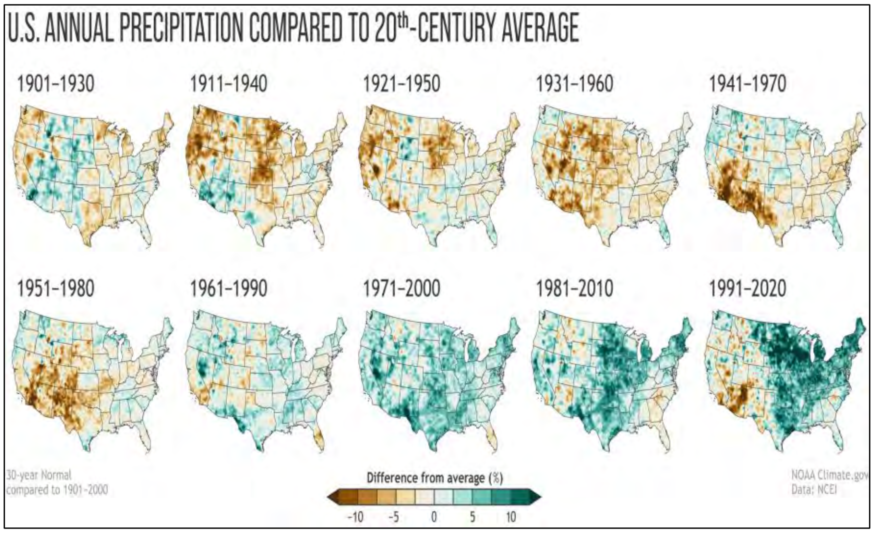


Figure 2 U.S. Annual Precipitation compared to 20th-Century Average

1.0 INTRODUCTION

Cache County and Box Elder County have, for many years, sponsored a winter cloud seeding program over portions of the high-elevation watersheds within each county. The program continued this past winter with the goal of augmenting the natural precipitation in mountainous areas of each county. Statistical analysis of cloud seeding effectiveness in past years has generally indicated an estimated 5-15% increase in winter precipitation and snowpack in the project target areas.

Box Elder and Cache Counties again contracted with North American Weather Consultants, Inc. (NAWC) for the operational cloud seeding services for their mountain watersheds during the 2022-2023 winter season. NAWC has been active in cloud seeding since 1950, with operational programs in Utah since the mid-1970s, and is the longest standing private weather modification company in the world. The State of Utah, through its Division of Water Resources (UDWR) regulates cloud seeding activities within Utah and provides cost sharing funds to project sponsors.

The target area of the program consists of the mountainous portions of Cache and Box Elder Counties above approximately 6,000 feet MSL. These areas represent significant snowpack accumulation zones, which provide substantial spring and summer streamflow. Figure 1.1 shows the average annual precipitation for the State of Utah, delineating these higher-yield areas.

Utah law requires both a license and a project-specific permit be issued to the organization conducting the cloud seeding. The law also requires that a notice of the intent be made available to the public prior to the start of a cloud seeding project. NAWC complied with these requirements in the conduct of the program.

This report covers the operational cloud seeding conducted over the project watersheds during the 2022-2023 winter season. Section 2 contains a brief background on cloud seeding technology and the design of the seeding program. Section 3 discusses the types of real-time and forecast meteorological data that are used for conduct of the seeding programs. Section 4 summarizes the seeding operations conducted this past season. Section 5 details statistical evaluations of the effects of the cloud seeding program. A summary and recommendations for future seasons are given in Section 6.

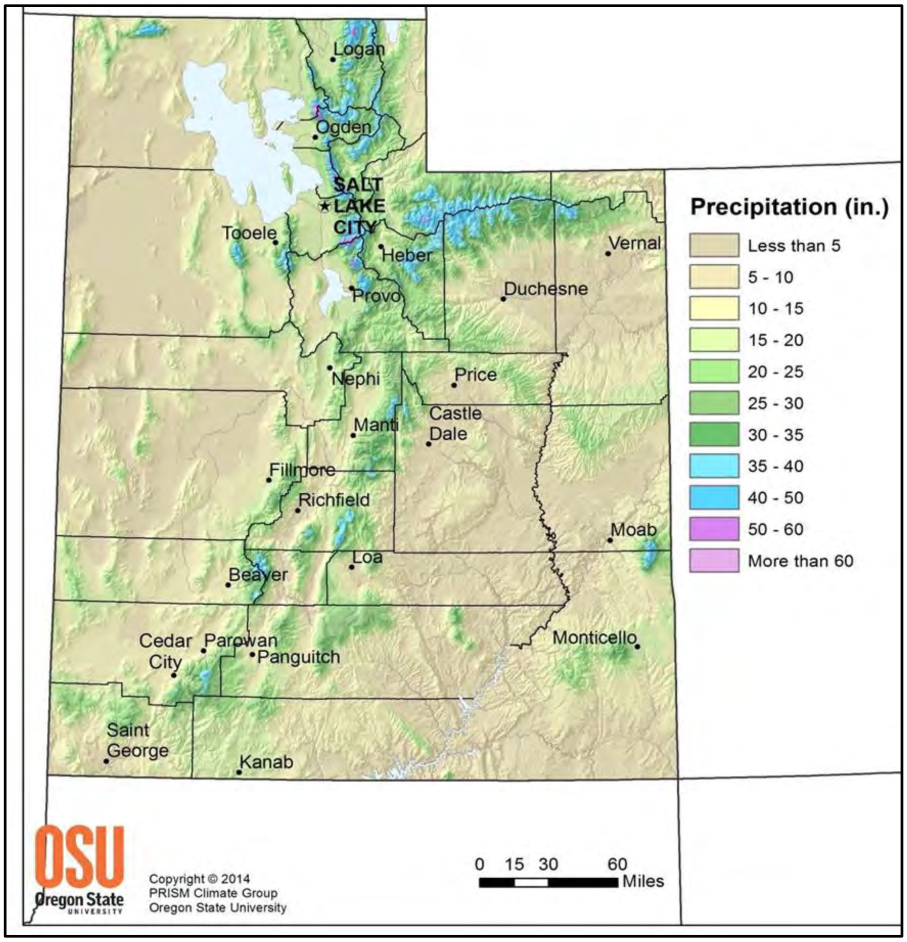


Figure 1.1 **Average annual precipitation for Utah, 1981-2010**

2.0 PROJECT DESIGN

2.1 Background

The operational procedures used in this cloud seeding project have been found to be effective during many years of wintertime cloud seeding in the mountainous regions of Utah. The results from this particular operational seeding program in northern Utah have consistently indicated increases in wintertime precipitation and snowpack water content during the periods in which cloud seeding was conducted.

2.2 Seeding Criteria

It is necessary that the silver iodide crystals become active upwind of the crest of a mountain barrier (i.e., the crest within the target area or defining its downwind boundary) so that the available supercooled liquid water (SLW) in the precipitation formation zone can be effectively converted to ice crystals, with enough time for the crystals to grow to snowflake size and precipitate within the intended target area. If the AgI crystals take too long to become active, or if the temperature upwind of the crest is too warm, the silver iodide crystals will pass from the generator through the precipitation formation zone and over the mountain crest without freezing additional water cloud droplets. Thus, an important task for the project meteorologists is to identify the seedable portions of the cloud systems which traverse the project area.

Operations have utilized a selective seeding approach, which has proven to be the most efficient and cost-effective method, providing the most beneficial results. Selective seeding means that seeding is conducted only during specific time periods, and in specific locations, where it is likely to be effective. This decision is based on several criteria which determine the seedability of the storms affecting the region. These criteria deal with the nature of the atmosphere (temperature, stability, wind flow, and moisture content) both in and below the clouds, and are summarized in the following list.

Winter Orographic Ground Based Seeding Criteria

- Cloud bases are near or 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 upward vertical transport 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 700mb level (approximately 10,000 feet) expected to be warmer than -15°C (5°F).

Use of this focused seeding methodology has yielded consistently favorable results at very attractive benefit/cost ratios.

2.3 Equipment and Project Set-Up

In November 2022, NAWC installed ground-based cloud seeding equipment at locations which are typically upwind (generally on the west sides) of the mountain ranges in Cache County, and in easternmost and northwestern Box Elder County. These mountain ranges generally have crest elevations between 7,000 and 8,000 feet, although some peaks exceed 9,000 feet. The locations of the mountain ranges in northern Utah are shown in Figure 2.1. The intended target area of the cloud seeding program includes the areas that exceed 6,000 feet in elevation. The locations of the cloud nuclei generator (CNG) sites are also shown in Figure 2.1.

Two new remotely operated sites were installed in support of the program in February 2023, one near Richmond and the other a high-elevation site southeast of Huntsville. These are higher output sites than the manually operated equipment, and the total seeding hours for the remote sites was counted separately from that of the manual sites.

The cloud seeding equipment at each manually operated site consists of ground-based cloud nuclei generator units, each connected to a propane gas supply. Each unit contains an eight-gallon tank for the seeding solution, an attached flow regulator, a burner head, and a windscreen. The propane gas supply is connected to the CNG by copper tubing. NAWC's CNGs are a field-proven standardized design. NAWC uses a fast-acting seeding solution, in order to provide maximum benefit for the target areas. The seeding solution consists of two percent (by weight) silver iodide (AgI), complexed with very small amounts of sodium iodide and para-dichlorobenzene in solution with acetone. During operation, the propane gas pressurizes the solution in the tank while also providing a heat source to vaporize the seeding solution. After propane flowing through the burner head is manually ignited, a metering valve is opened and adjusted, spraying the seeding solution into the propane gas flame where the silver iodide is vaporized. When the vapor comes into contact with cold air, it crystallizes to form microscopic silver iodide particles. The seeding units are manually operated and, when properly regulated, consume 0.12 gallons of solution per hour. Microscopic silver iodide crystals are emitted from each CNG at a rate of approximately 8 grams per hour via combustion of the 2% solution. These crystals closely resemble natural ice crystals in structure. Their activity as ice forming nuclei is temperature sensitive, occurring at temperatures < -5°C (23°F). The number of ice crystals activated per gram will vary as a function of temperature, with more nuclei becoming active at colder temperatures. The activity of these nuclei is converting supercooled liquid water droplets within the clouds to ice particles, which, given the right conditions, can grow to precipitation sized particles.

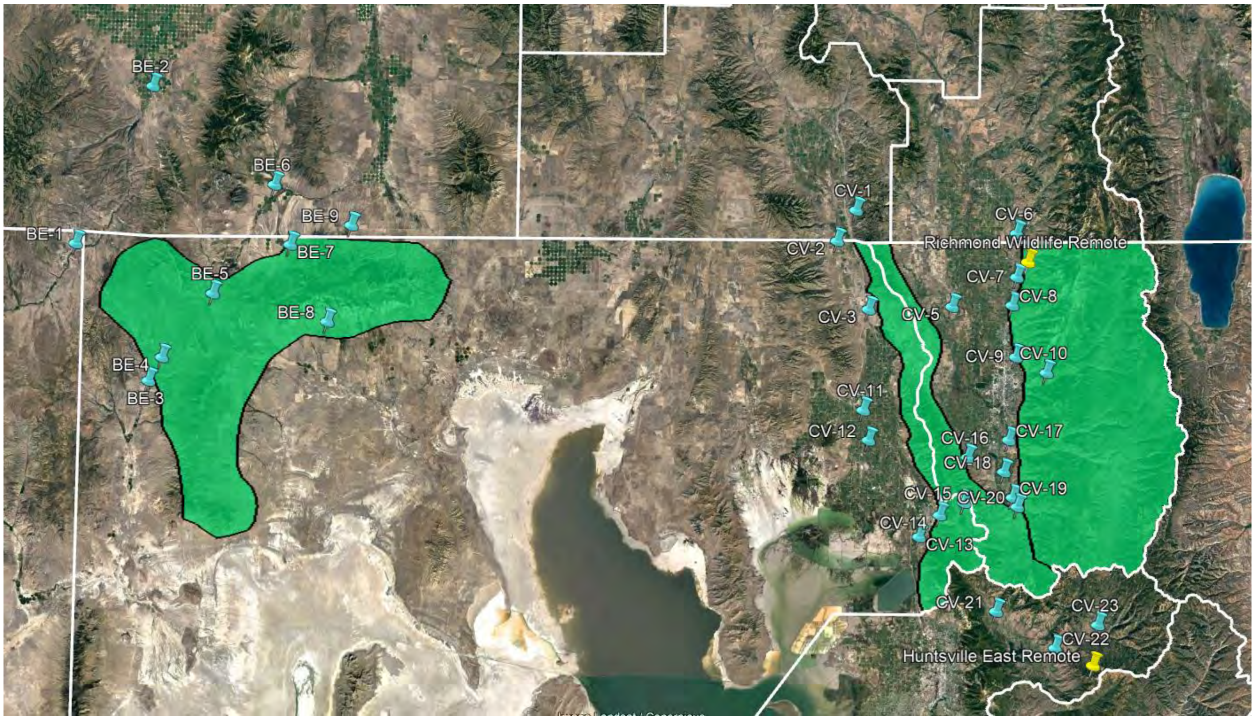


Figure 2.1 **CNG sites and seeding target areas for the 2022-23 Northern Utah Program; yellow pins are the new remotely operated sites**

There were 31 available manually operated sites with cloud nuclei generators, located in Cache County, Box Elder County, and Weber County for seeding the target areas. Two new remotely operated sites were added to these during the season. Three CNGs were located on the Idaho side of the state line, two for seeding northwestern Box Elder County and one to target the more eastern portions of the program. Figure 2.1 shows the CNG site locations and target area for the project. These are essentially the same site locations that were utilized during the previous seasons. Pertinent site information is listed in Table 2-1.

The process of choosing seeding sites involves studying topographical maps and identifying general areas most suitable, considering the typical wind flows and terrain effects during storm periods. Most sites are restricted to populated areas, since most cloud nuclei generators are manually operated.

Most winter storms that affect the northern Utah mountains are associated with synoptic weather systems which move into Utah from the southwest, west, or northwest. They often consist of a frontal system and/or an upper trough, with south or southwesterly winds ahead of these features. In meteorology, wind directions are reported as the direction the wind is blowing from, in advance of the system. As the front and/or trough moves through the area, the wind flow typically becomes more northwesterly as time passes. Clouds and precipitation may precede, as well as follow, the front/trough passage, and thus seeding sites are situated to enable seeding operations in southwesterly, westerly, or northwesterly flow situations.

Table 2-1
Cloud Seeding Nuclei Generator Sites

ID	Site Name	Elevation (ft)	Lat (N)	Long (W)
BE-1	Trout Creek	5070	41° 57.00'	114° 04.00'
BE-2	Oakley	4570	42° 14.04'	113° 53.55'
BE-3	Grouse Greek	5334	41° 42.54'	113° 52.94'
BE-4	Grouse Creek N	5484	41° 45.08'	113° 51.07'
BE-5	Lynn	5930	41° 52.00'	113° 44.00'
BE-6	Almo	5340	42.10.00’	113.35.20’
BE-7	Yost	5986	41° 57.40'	113° 33.01'
BE-8	Rosette	5640	41° 49.29'	113° 27.49'
BE-9	Standrod	5811	41° 59.61'	113° 24.34'
CV-1	Malad South	4450	42° 02.00’	112° 12.00’
CV-2	Portage	4500	41° 58.71'	112° 14.68'
CV-3	Plymouth	4417	41° 51.45'	112° 10.09'
CV-5	Newton	4662	41° 51.78'	111° 58.12'
CV-6	Cove	4577	41° 59.65'	111° 48.81'
CV-7	Richmond	4600	41° 54.96'	111° 48.84'
CV-8	Smithfield	4694	41° 51.96'	111° 49.50'
CV-9	Logan	4580	41° 46.41’	111° 48.94’
CV-10	Logan Canyon	4971	41° 44.77'	111° 44.72'
CV-11	Tremonton	4295	41° 40.69'	112° 10.75'
CV-12	Bear River City	4265	41° 37.49'	112° 09.96'
CV-13	Perry	4404	41° 27.21'	112° 02.67'
CV-14	Brigham City	4690	41° 29.54'	111° 59.77'
CV-15	Mantua	5200	41° 30.89'	111° 56.34'
CV-16	Wellsville	4884	41° 35.72'	111° 55.80'
CV-17	Hyrum	4816	41° 37.58'	111° 49.92'
CV-18	Paradise	4875	41° 34.19'	111° 50.62'
CV-19	Avon	5059	41° 31.45'	111° 49.39'
CV-20	Avon South	5079	41° 30.47'	111° 48.70'
CV-21	Liberty	5107	41° 19.31'	111° 51.70'
CV-22	Huntsville	5066	41° 15.37'	111° 43.21'
CV-23	Red Rock Ranch	5473	41° 17.86'	111° 37.17'
	Richmond remote	5000	41°56.5’	111°47.2’
	Huntsville SE	7700	41°14.8’	111°37.8’

2.4 Suspension Criteria

NAWC conducts its projects within guidelines adopted to ensure public safety. Accordingly, NAWC has a standing policy and project-specific procedures for the suspension of cloud seeding operations in certain situations. Those criteria can be found in Appendix A and have recently been updated in coordination with the Utah Division of Water Resources. The criteria are an integral part of the seeding program. While the designated SNOTEL sites used as criteria for this program did not officially quite reach their suspension criteria, the excessive snowpack at lower elevations sites (far exceeding anything in the recorded record in some cases) prompted a suspension of the program near the end of the season, on March 24. Concerns about snowmelt flooding had become fairly widespread in northern Utah by that point in the season, and subsequent storms added additional significant snowpack at all elevations into early April which accentuated those concerns.

3.0 WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

NAWC maintains a fully equipped 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, radar information and weather cameras. NAWC's meteorologists have access to all meteorological products from their homes, allowing continued monitoring and conduct of seeding operations outside of regular business hours. This wide variety of available products and information helps NAWC meteorologists to determine when conditions are appropriate for cloud seeding.

Figures 3.1 – 3.4 show examples of some of the available weather information that was used in this decision-making process during the 2022-2023 winter season. These include weather radar images, satellite images, and surface wind and temperature maps. Figure 3.4 illustrates the predictions of ground-based seeding plume dispersion using the National Oceanic and Atmospheric Administration's HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model. This model provides forecasts of the horizontal and vertical spread of a plume from potential ground-based seeding sites in real-time, based on wind fields contained in the weather forecast models.

Global and regional forecast models are a cornerstone of modern weather forecasting, and an important tool for operational meteorologists. These models forecast a variety of parameters at different levels of the atmosphere, including winds, temperatures, moisture, and surface parameters such as accumulated precipitation. An example of a display is shown from the GFS model (Figure 3.5).

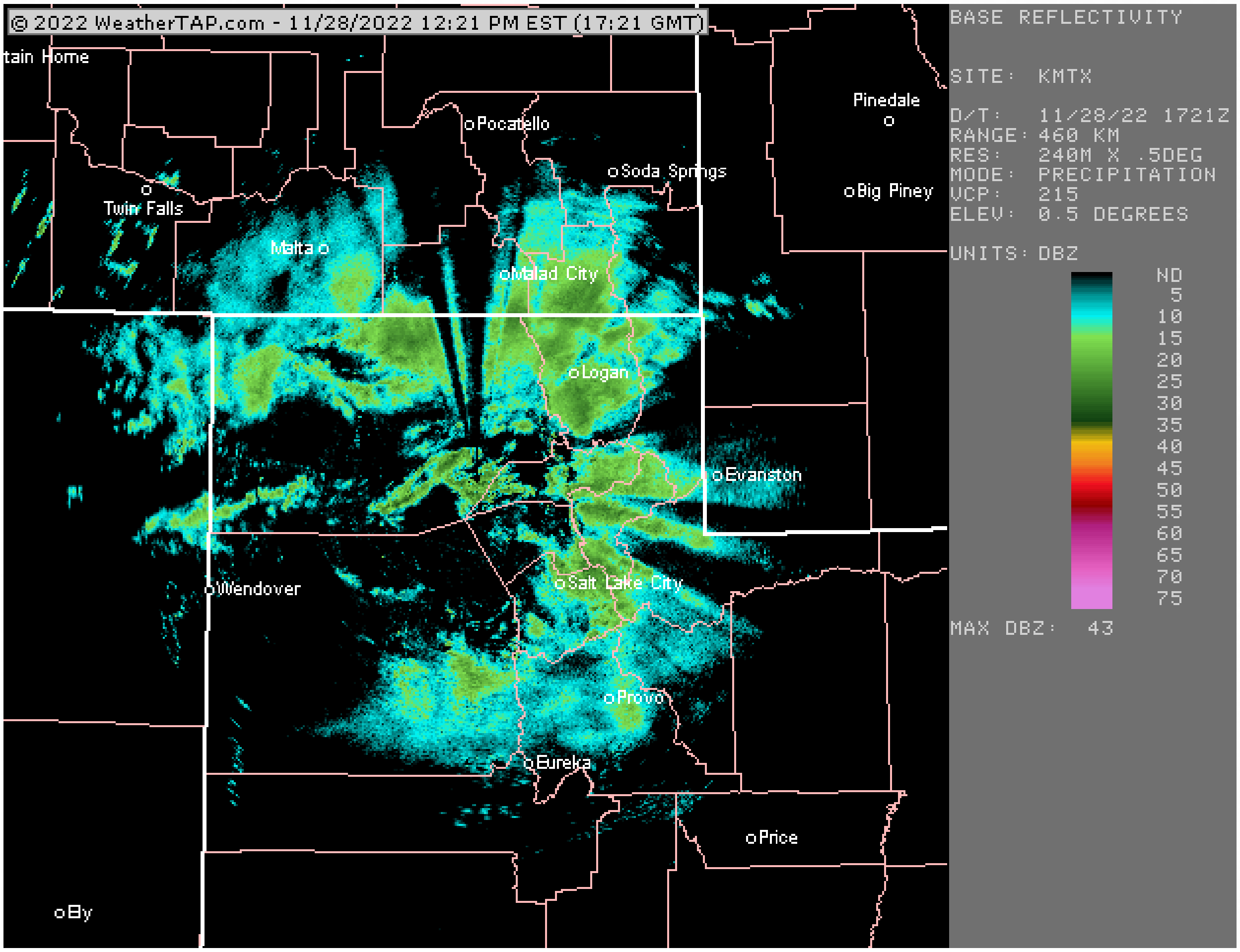


Figure 3.1 Weather radar image during a storm event over northern Utah on November 28, 2022

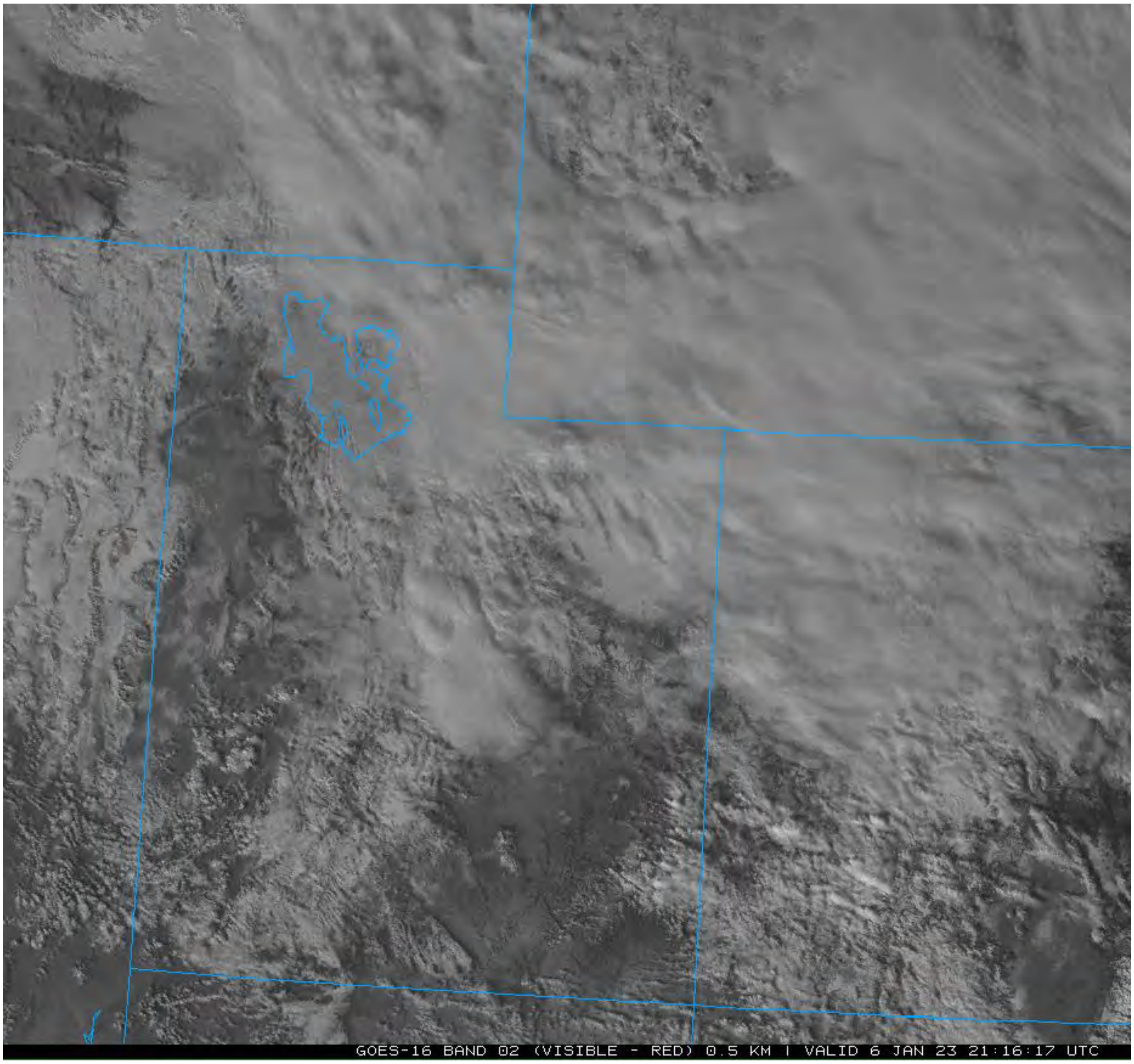


Figure 3.2 Visible spectrum satellite image on January 6, 2023

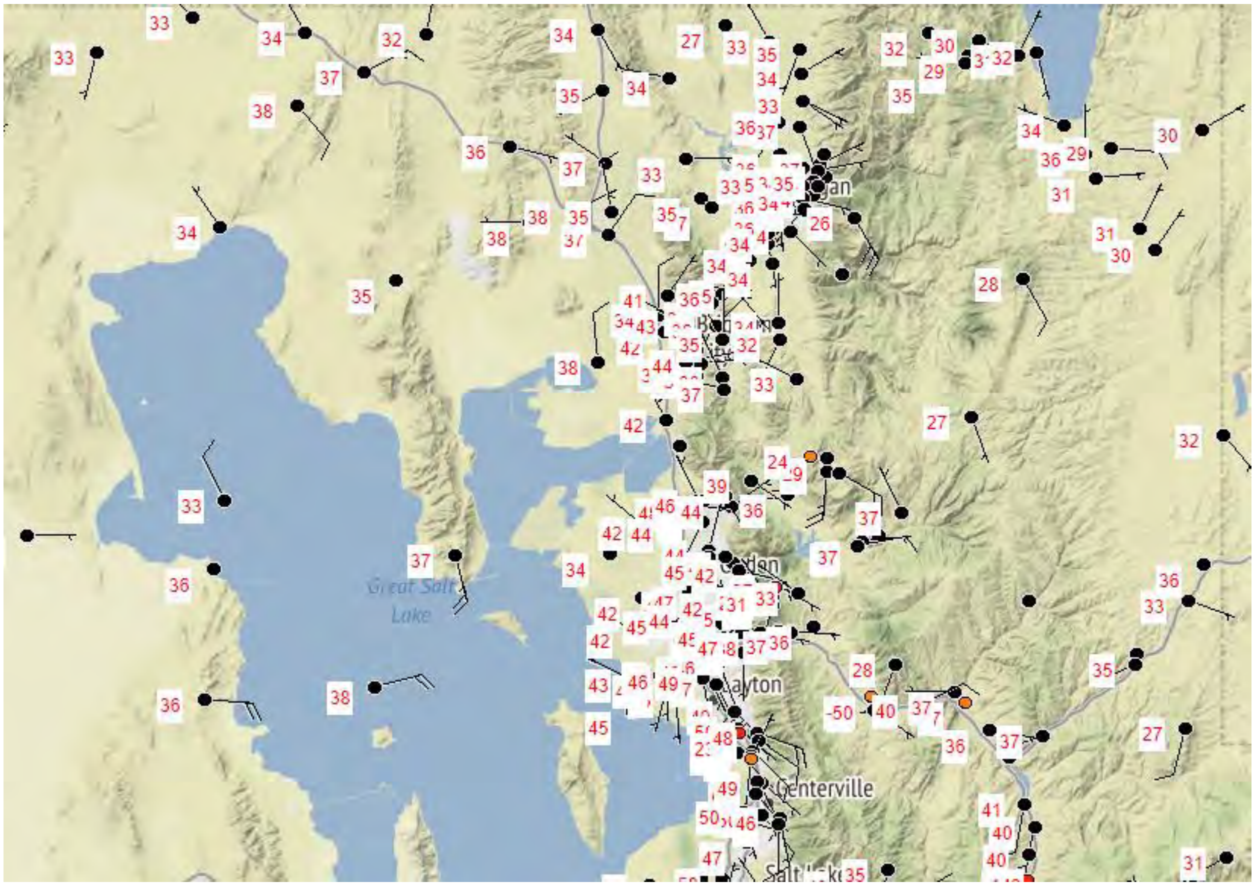


Figure 3.3 Mesowest surface data map on January 10, 2023. Surface observations are important for diagnosing low-level wind patterns and mixing.

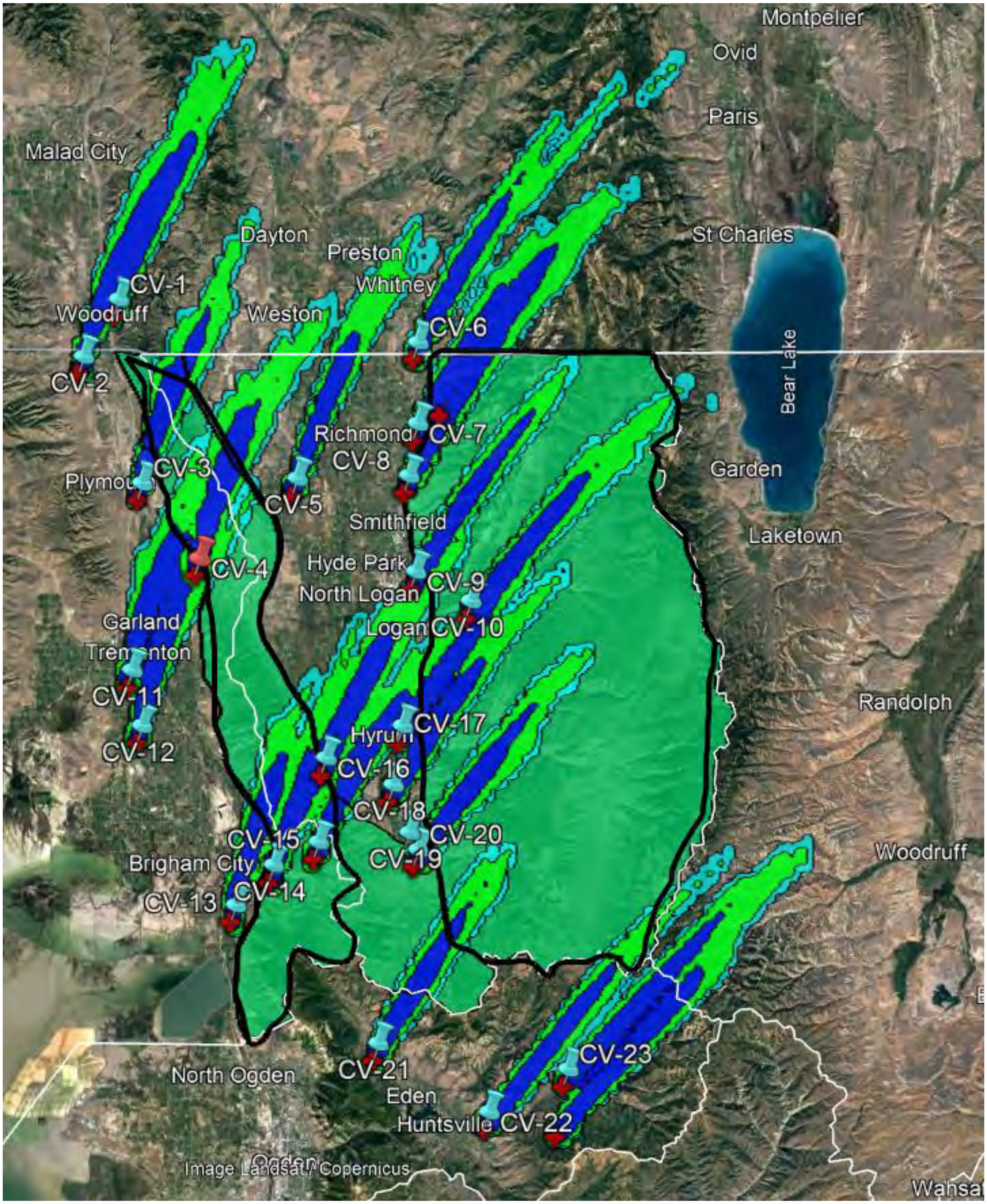


Figure 3.4 HYSPLIT plume dispersion forecast for a storm event on the evening of February 26, 2023, for all potential seeding locations that can be used to eastern portions of the Northern Utah seeding program (target shaded in green). Only some of these sites were utilized in this event.

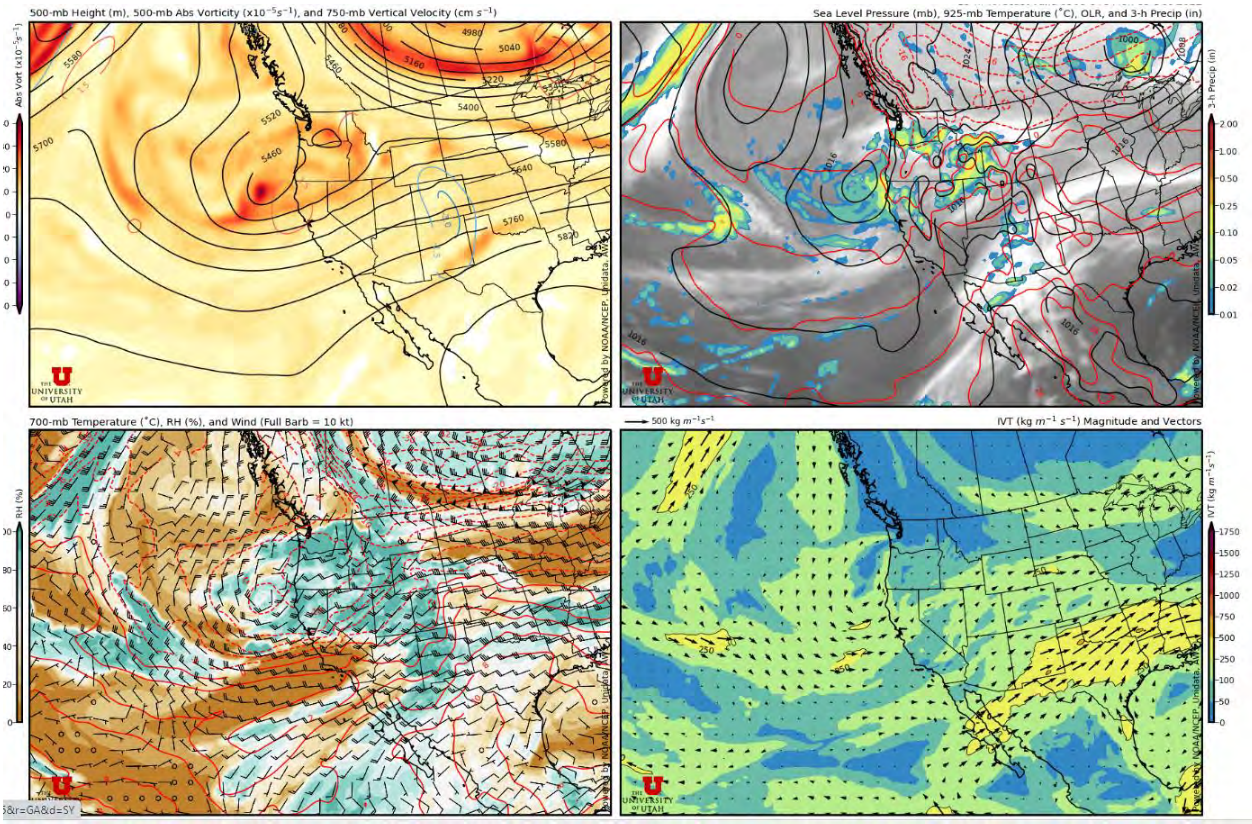


Figure 3.5 GFS (Global Forecast Systems) forecast data plot for a storm event on December 4, 2022.

4.0 OPERATIONS

The 2022-2023 seeding program in Box Elder and Cache Counties began on December 1, 2022 and was contractually scheduled to end on March 31, 2023. However, extremely high snow water content in and around the seeding target areas, particularly at lower to mid elevation sites, resulted in a suspension of seeding operations on March 24. During the 2022-2023 season, there were 21 seeded storm periods conducted on portions of 35 days. Six storm events were seeded in December, four in January, four in February, and seven in March. A cumulative 2,360 operational hours were conducted from all manually operated generator sites during the season. Early in 2023, a couple of new remotely operated sites were installed in support of the program as described in an earlier section. An additional 43.5 generator hours of seeding was conducted from these sites. Table 4-1 shows the dates and seeding generator usage for the storm events, and Appendix B shows seeding times for individual generator sites. Figure 4.1 is a graph of seeding operations (CNG usage) this season.

Table 4-1
Storm Dates and Number of Generators Used,
2022-2023 Season

	Date(s)	No. of Generators Used	No. of Hours
1	December 1-2	11	93
2	December 4-5	5	45.25
3	December 11-12	8	125.25
4	December 13	3	16.75
5	December 21	16	121.25
6	December 27-29	15	172.75
7	January 5-6	16	246.5
8	January 10-11	20	276.75
9	January 17	2	14.5
10	January 27-28	13	186.75
11	February 5-6	3 + 1 remote	24.5 + 3.5 remote
12	February 8	6 + 1 remote	17.5 + 2.25 remote
13	February 21-22	19	183.75
14	February 26-27	12 + 1 remote	338.75 + 23.25 remote
15	March 3	3 + 1 remote	11.75 + 2.75 remote
16	March 4-5	3	44.5
17	March 5-6	9	49
18	March 15	2 + 1 remote	5.5 + 3.75
19	March 20-21	15 + 1 remote	178.25 + 8 remote
20	March 22-23	6	115.5
21	March 24	10	92.25
		Season Total	**2360.25**

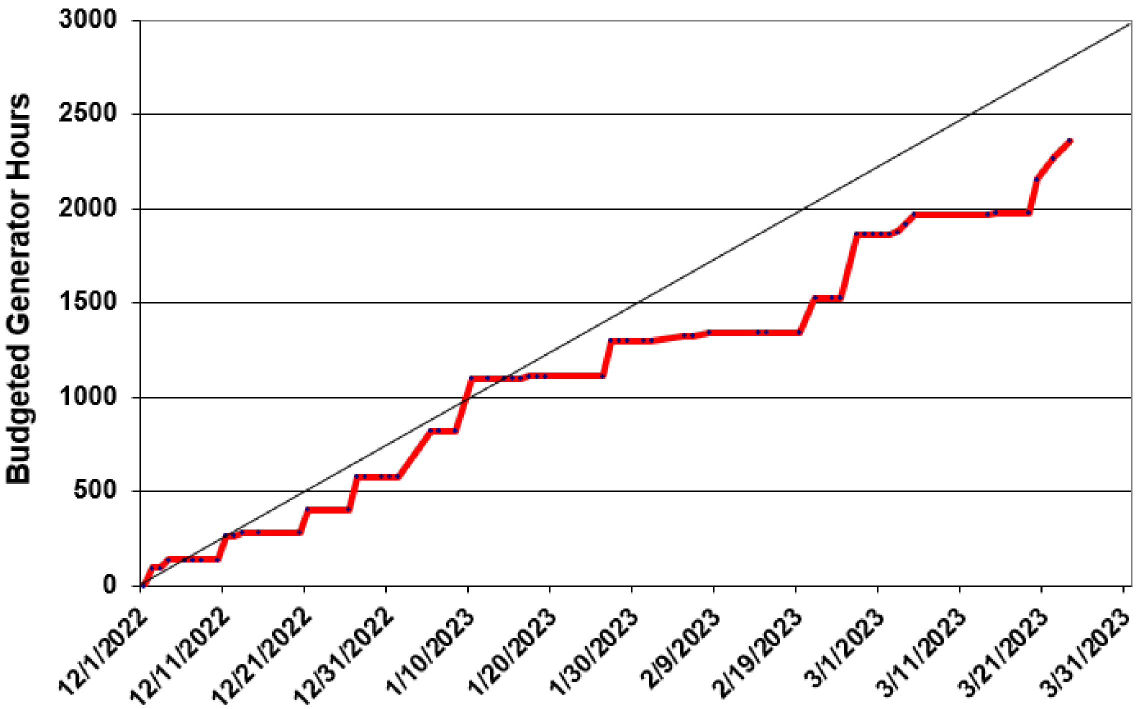


Figure 4.1 **Seeding operations during the 2022-2023 season (red), compared with a linear usage of total budgeted hours (diagonal black line).**

Precipitation and snowpack were far above average in northern Utah during the 2022-2023 winter season. Snowpack in the Bear River Basin on April 1, 2023 averaged 164% of normal (median) with about 143% of the normal (median) water year precipitation to date. The comparatively lower value for water year precipitation was due to a very high percentage of precipitation since October 1 falling as snow instead of rain, and consistently cold temperatures during the winter season which produced an abnormally large (and record-breaking) amount of lower and mid elevation snowpack in particular. Figures 4.2 to 4.4 show snow water content and precipitation this season, compared to various historical measures, at the Tony Grove Lake, Bug Lake, and Monte Cristo SNOTEL sites.

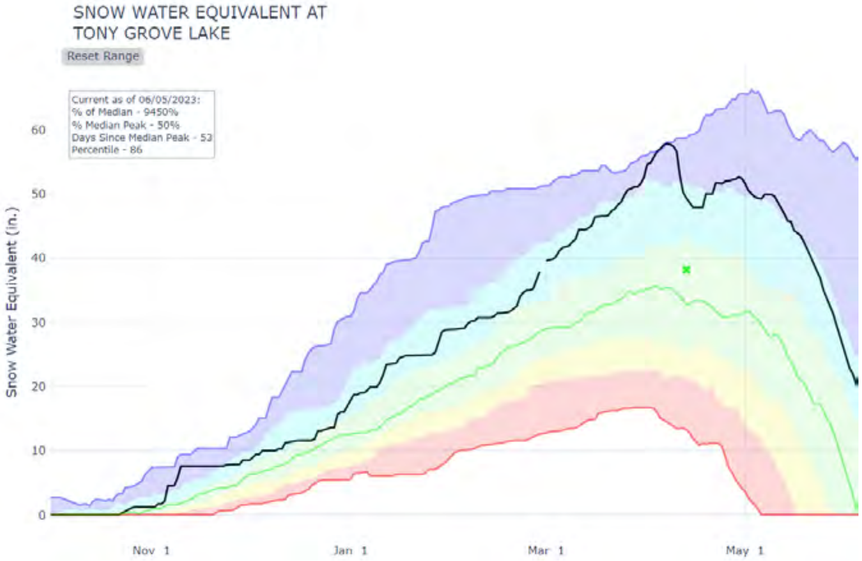


Figure 4.2 **SNOTEL snow and precipitation plot for October 2022 through May 2023 for Tony Grove Lake, UT. Black line is the current water year, and green represents the median values. Purple and red lines represent maximum and minimum historical values, respectively.**

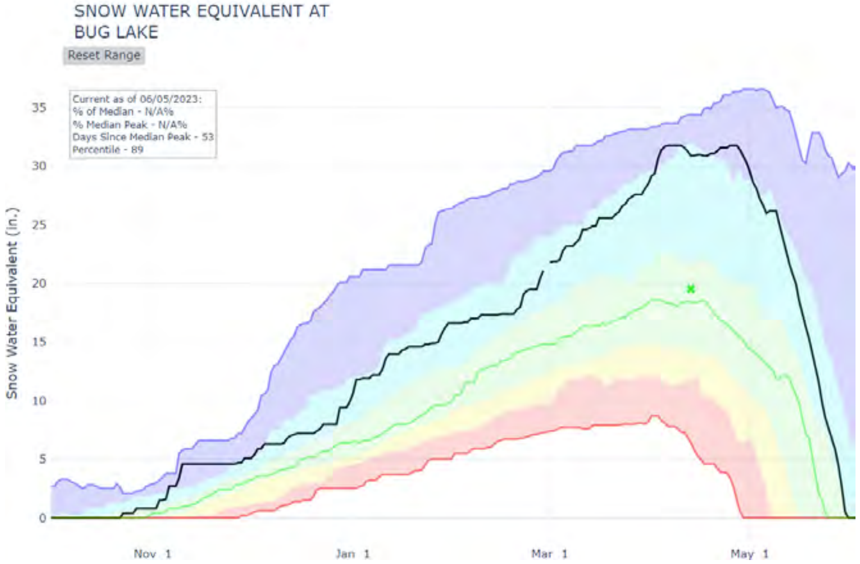


Figure 4.3 **SNOTEL snow and precipitation plot for October 2022 through May 2023 for Bug Lake Lake, UT. Black line is the current water year, and green represents the median values. Purple and red lines represent maximum and minimum historical values, respectively.**

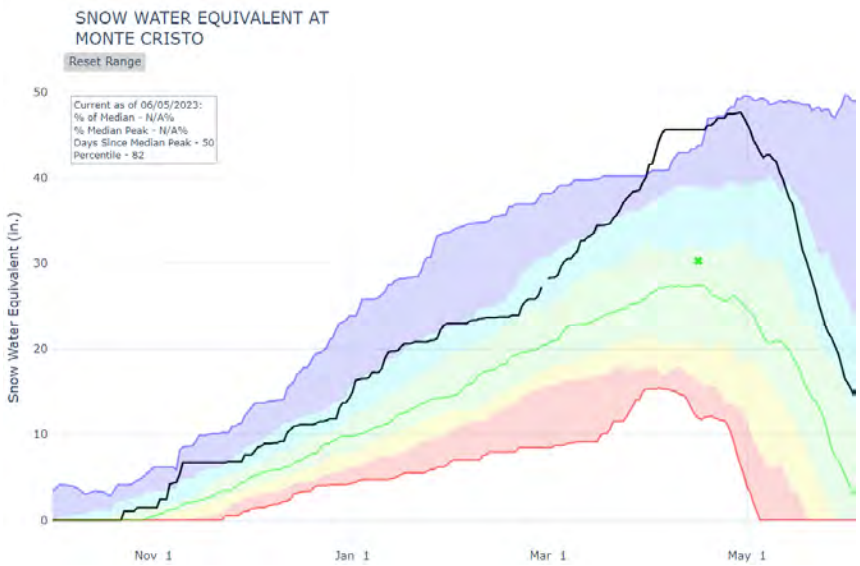


Figure 4.4 SNOTEL snow and precipitation plot for October 2022 through May 2023 for Monte Cristo, UT. Black line is the current water year, and green represents the median values. Purple and red lines represent maximum and minimum historical values, respectively.

4.1 Operational Procedures

During the operational period, the project meteorologist monitored each approaching storm with the aid of continually updated online weather information. If the storm parameters met the seedability criteria presented in Section 2 and if no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators were ignited and then adjusted as evolving conditions required. Seeding continued as long as conditions were favorable and precipitating clouds remained over the target area. The operation of the seeding sites is not a simple “all-or-nothing” situation. Individual seeding sites are selected and run based on their location, and targeting considerations based on storm attributes.

4.2 Operational Summary

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

December 2022

The first week of December started off with a cold trough moving eastward across Oregon, Nevada, and Idaho, and its associated cold front clipping Northern Utah overnight December 1st and 2nd. The front continued to accelerate overnight, bringing low-density snow showers to the area. A narrow band of supercooled liquid water (SLW) persisted along the frontal boundary, with the majority of precipitation coming from a high cloud deck, as lower-level moisture was limited in this storm system. Wind direction following the front began as westerly, eventually shifting to northwesterly, providing suitable conditions for seeding. Activation of CNG sites began the night of December 1st at 2200 MST, and operations continued until 0800 on December 2nd MST when precipitation ended. This storm left 3-6 inches of snow in most valleys with 0.5-0.9 inches of snow-water content in the eastern portions of the program area.

On December 3rd, a large and vigorous closed low was observed over the California/Oregon coastline, and could be seen dropping slowly southward. Utah remained dry this day, although areas of mid/high-latitude clouds were observed with southwesterly flow, and 700 mb temperatures warmed above -5 C. On the morning of December 4th, the closed low remained centered and nearly stationary over the far northern California coast. The 700 mb level sustained west-southwesterly winds, with following lower-level winds shifting to mostly westerly throughout the morning and afternoon of the 4th. Lower levels across Utah remained very stable during this time. Despite the less-than-ideal seeding conditions, winds aloft shifted westerly the evening of the 4th bringing a brief period of moisture and snowfall to the target area. Seeding began at 1700 MST on the 4th and ran until 0700 on the 5th, shortly after snowfall ended. Precipitation totals for the Northern Utah target area over December 4th-5th ranged from 0.2 – 0.7 inches of water content.

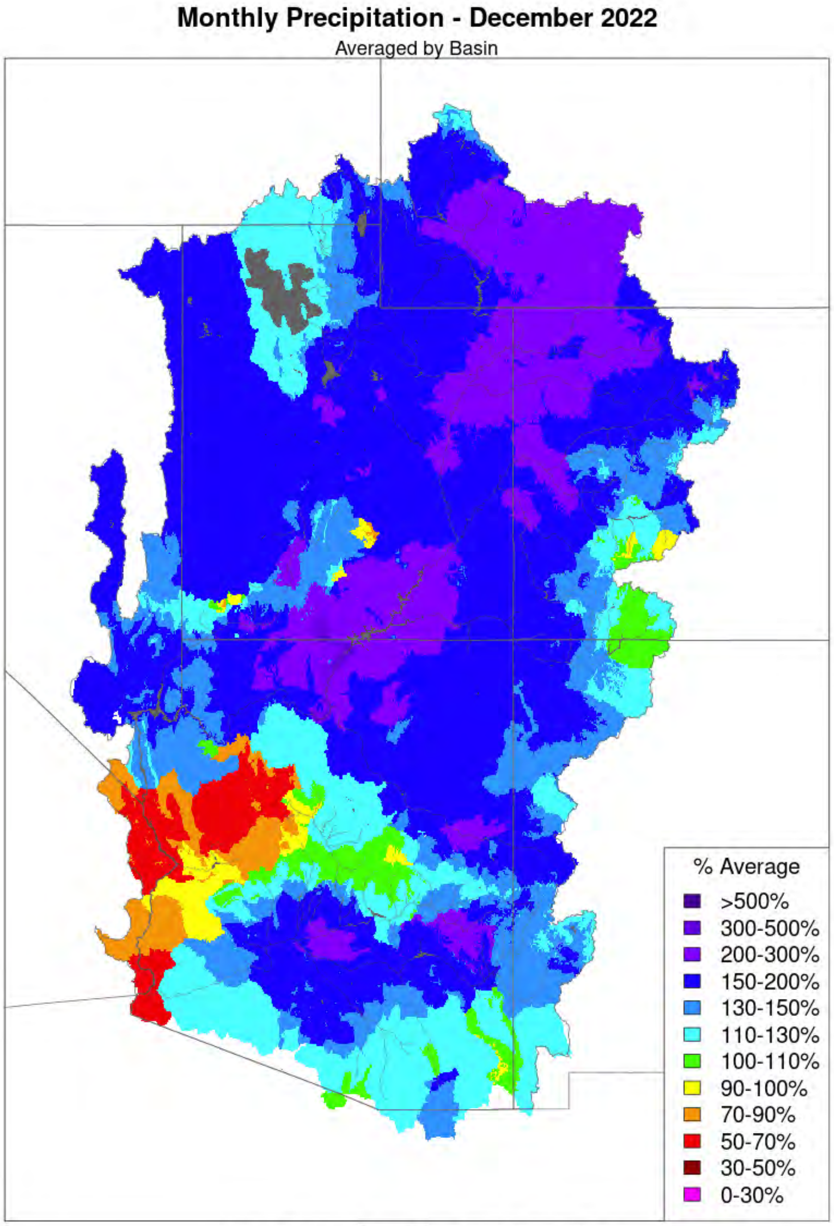
After almost a week of dry weather over Utah, a deep trough developed along the northern/central California coast. The trough was observed pushing southeastward on December 11th, accompanied by a baroclinic band of intensifying precipitation from a higher cloud deck, and south-southeast surface and 700 mb winds over northern Utah around 1600 MST. A frontal boundary was observed near the Utah/Nevada border with consistently south-southeasterly upper-level winds that evening as well. This frontal system moved mostly through central Utah, only partially clipping the Northern Utah target area. Southern CNG sites were activated on December 11th around 1715 MST for the eastern target areas, with precipitation picking up late that evening, and largely ending overnight. The morning/afternoon of December 12th experienced a shift in wind direction to primarily westerly, as well as scattered snow showers throughout the day. 700 mb temperatures were around -10° C at 1400 MST, and CNG sites continued running until the evening of the 12th around 1915 after snow showers had tapered off and higher clouds were no longer seedable. The northern Utah target area accumulated 0.9-1.3 inches of precipitation (water content) over the 11th and 12th.

This storm system of December 11-12 continued through December 13th, with northerly flow bringing light snowfall to Northern Utah and 700 mb temperatures around -12° C. Nearly all precipitation through the afternoon came from a low-level cloud deck that appeared optimal for seeding operations, which began at 1200 MST on the 13th. Later that evening, winds began shifting more northwesterly, but were still fairly docile near the surface, and supercooled liquid water (SLW) was also quite minimal. Radar showed light, uniform precipitation up extending up to 13,000 feet throughout the evening, so some Cache Valley CNG sites continued to run until about 2030 MST. By that time the clouds were dispersing and seeding operations ended, leaving an accumulated total of 0.1-0.2 inches of precipitation on December 13th.

A deep arctic trough centered to the north was observed pushing southeastward the morning of December 21st, with a baroclinic zone developing near northern Utah. Strong southwesterly surface winds and northwesterly upper-level winds brought increasing low to mid-level moisture, orographic snowfall, and 700 mb temperatures near -8 to -10° C. By the late morning on the 21st, most of the remaining low-level stability from the prior week was mixing out, with decent SLW values and orographics. These conditions provided a good environment for activation of upwind CNG sites which began around 0900 MST that morning, but strong winds of roughly 40 knots at the -5° C temperature level made targeting a challenge. Orographic and weakly convective clouds brought snow showers through the afternoon and early evening, and maintained good conditions for seeding operations. While the frontal boundary wasn't dramatic, arctic air behind an initial cold front filtered into far northern Utah during the evening, and mid to upper-level winds remained very strong from the northwest with gusts between 60-90 mph reported in portions of the Wasatch range. Lower-level winds gradually shifted from westerly to northwesterly, and the 700 mb temperature was near -10° C. Later in the evening, however, cold arctic air made its way southward from Idaho into Utah, and fairly dramatic drying and cooling was observed. Seeding operations ended around 2100 MST on the December 21st, with roughly 0.5-1.0 inches of accumulated precipitation during this event.

A large and vigorous trough centered over the pacific northwest on the 27th brought about the last storm system of December in Utah, with a large band of subtropical moisture affecting much of Utah and the western United States. The 700 mb level experienced southwesterly winds during the day, and temperatures near 0° degrees C. A band of convection precipitation developed over southern Idaho in the early evening and pushed across Northern Utah on the night of the 27th, resulting in suitable conditions for seeding operations which began at 1945 MST for both the western and eastern portions of the target area. As the trough core moved eastward overnight, 700 mb dropped to below -6° C and winds remained westerly at roughly 40 knots. Moving into the early morning of the 28th, 700 mb wind speeds decreased to around 25 knots and the direction shifted to more northwesterly. Scattered convective showers were observed in this northwesterly flow mainly during the afternoon hours of the 28th, with 700 mb temperatures near -12° C at the time. Seeding operations ended by midday, but were resumed shortly at several sites in the southern half of eastern target areas during the mid to late afternoon. Around 1900 MST, valley winds became light and areas of light snowfall tapered off and mostly ended that night. All but one CNG site was stopped at this time, with the Logan CNG site running until 0700 on the December 29th when skies cleared. This storm system generated 1.0-2.5 inches of precipitation over the northern Utah target areas.

Figure 4.5 shows December precipitation across the area as a percentage of normal (median) values. The northern Utah target areas received anywhere from about 110 – 200% of the normal December precipitation.



Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

Figure 4.5 **December 2022 precipitation, percent of normal**

January 2023

The first week of January began with a large storm system moving out of California into the Great Basin on the 5th. This storm exhibited warm advection in southwestern flow, with 700 mb temperatures rising to around -5°C. Many areas experienced light precipitation beginning in the late afternoon/early evening, but valley conditions in parts of northern Utah were still quite stable with valley surface temperatures near/below freezing in the far north. Other areas mixed out quite well, however, and seeding conditions were met in the late evening. CNG sites were activated around 1900 MST on January 5th, and low-level winds remained primarily southerly through most of the night. On the morning of the 6th, the main low-pressure center had lifted northeast to near southern Montana, and low-level winds in areas such as Cache Valley remained light/variable, and still primarily from the south. In areas above, however, winds had turned primarily westerly. The valley continued to have light showers of a rain-snow mix while 700 mb temperatures were near -7° C throughout the day of January 6. Seeding continued at some sites as long as 2000 MST. Precipitation amounts were mostly around 0.5 – 1.0 inches of water content in this event.

On January 10th, another forceful cold-core trough was observed pushing out of California and into the Great Basin. The trough, negatively tilted, reached southwestern Utah initially. A mild southerly flow pattern over Utah brought some remnants of a subtropical moisture plume which produced intermittent precipitation and 700 mb temperatures of near -4° C over northern Utah. By mid-evening on the 10th, a strong cold front aligned nearly due north-south was moving into far western Utah, with widespread precipitation just ahead of the frontal boundary. This initiated some convective activity as upper levels cooled down and lower levels remained moisture-ridden. These conditions allowed activation of some CNG sites in northwestern Box Elder County around 1700 MST, and as the front reached the eastern areas, allowed for activation of those CNG sites as well. Much of far northern Utah remained stable with colder surface temperatures throughout the day, but mixed out quite well with the arrival of the cold front in the evening. The morning of January 11th experienced light orographic snowfall in northwesterly flow and 700 mb temperatures near -10° C, but radar showed the end of snowfall around 1200 MST with satellite and visual observations showing the trough moving eastward, at which point seeding operations ended. Precipitation totals were mostly in the 0.5 – 1.2 inch range during the seeded portion of the event.

The third storm system in January developed similar to the previous two, with another trough moving from California into the Great Basin again on the 16th, though not as vigorous. The upper low center developed over southern Utah in the afternoon with active convection, and caused very light snow showers in the northern half of the state with winds evolving from mostly southerly to quite variable later in the day. 700 mb temperatures were near -8° C, but such variable winds made seeding possibilities questionable during the most of the day. During the evening of the 16th, however, a compact and very strong low center moved northeast across central Utah. By the morning of the 17th, the low became centered over southern/central Utah and caused patchy, disorganized showers over the state. There was some low-level stability in the north during the morning with surface temperatures in the upper 20s, north-northeasterly winds at lower levels and light, and variable southerly winds aloft. This situation allowed seeding operations at two sites to begin at 0800 MST that morning. By early afternoon, the snowfall had ended per radar, and seeding operations ended. Precipitation totals were light with this event, near 0.2 inches at most sites.

A trough was developing to the north on January 27th causing warm advection and westerly winds (southerly at low elevations). 700 mb temperatures were near -8° C, and light precipitation originated about 20,000 feet aloft in a higher cloud band in the morning per a vertical wind profile. Mesowest data showed improved valley mixing from southerly winds with near to above freezing surface temperatures in most lower valleys, and an HRRR cross section forecast showed modest amounts of liquid water between 800-600 mb. Around 1230 MST, seeding conditions were showing gradual improvement with better mixing and weak cold advection aloft, and southerly CNG sites were activated to begin seeding eastern portions of the target area. Later in the evening, valley winds remained light and variable while upper-level winds remained generally northwesterly. There was slight near-surface stability, but weak cold advection coincided with light orographic-type snowfall that evening around 1900 MST, and HRRR data showed more available liquid water and ideal seeding temperatures, so additional CNG sites were activated. The light snowfall continued throughout the night and into the morning of the 28th with a fairly low cloud deck and sustained light west-northwesterly valley winds. Most CNG sites were shut off the morning of the 28th, but a few persisted until the afternoon when conditions were no longer viable for any seeding. Precipitation totals were geneally near 0.5 inches with this event.

Figure 4.6 shows January precipitation as a percentage of the median. Most of northern Utah received from 150% to over 200% of the median values in January.

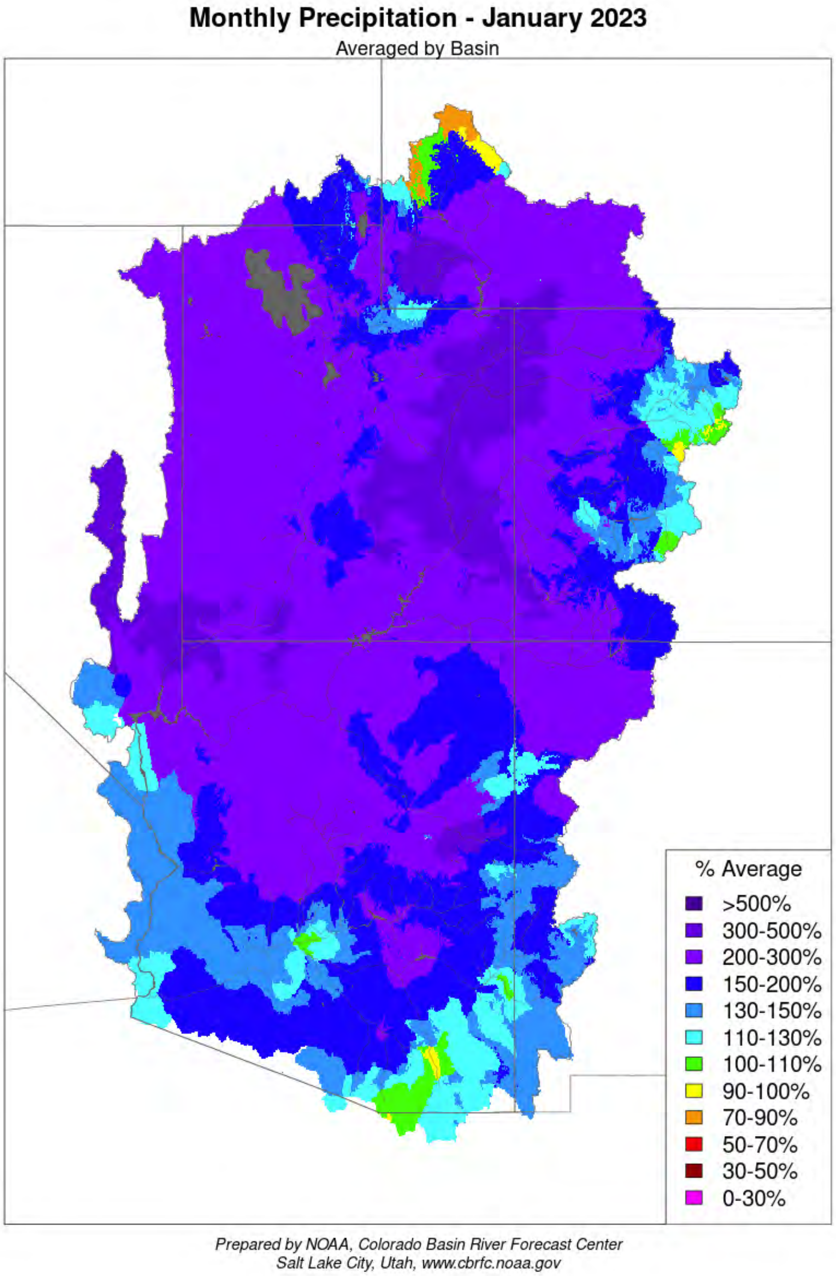


Figure 4.6 **January 2023 precipitation, percent of normal**

February 2023

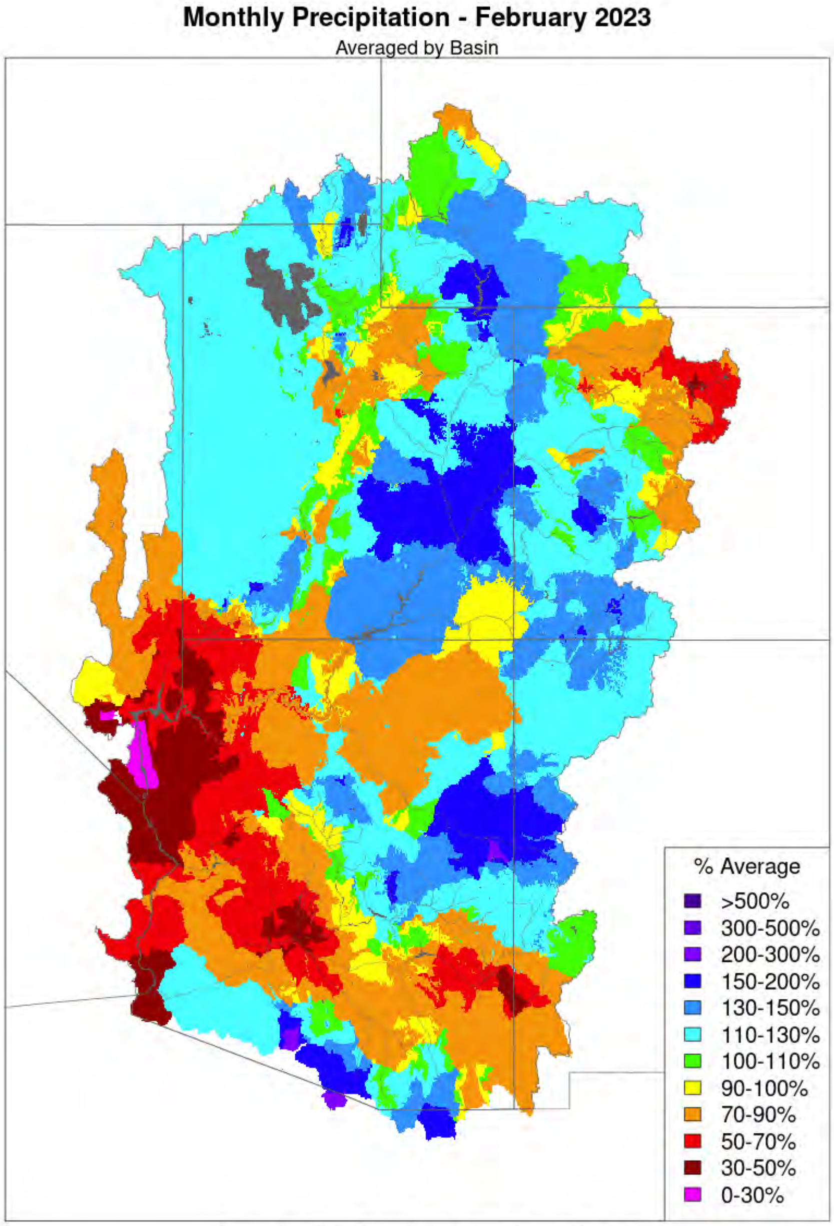
The first week of February began with a cold front moving across northern Utah during the late morning of the 5th, bringing with it widespread stratiform snowfall which originated at over 20,000 feet. An inversion event remained in place throughout the valleys, although temperatures were observed to have warmed near the freezing point, and 700 mb temperatures were near -8° C. Despite the widespread snowfall, there was limited supercooled liquid water near terrain, with most of it residing south of the eastern target areas where the snowfall was more moderate than over far northern Utah. A remote CNG site in Huntsville was activated at 1230 MST to utilize what seeding potential there was, but a second site wasn't activated until later that evening. Overnight, low-level stability slowly increased as valley temperatures cooled into the upper 20s in many areas, but the development of some light orographic snowfall with northerly winds on the morning of February 6th allowed for activation of a few more CNG sites, which were shut off in the mid-late afternoon. Precipitation totals were generally around a quarter to half inch with this storm event.

On February 8th, a cold trough centered over the northern Rockies was observed dropping southeast, with an associated cold front reaching far northern Utah midday. A mid-level cloud deck appeared in the late morning, and radar showed some precipitation developing over northern portions of eastern target areas, mostly below about 12,000 feet. Valleys were somewhat stable at this point, but mixed out quite well over the next few hours and experienced surface warming and strong mid-level cooling, with 700 mb temperatures between -10 to -14° C. These conditions, along with strong west-northwesterly flow, allowed for seeding operations at northern sites to begin at 1130 MST. In the early afternoon, a band of light snowfall shifted southward across Cache County, so the site array was adjusted to sites further south. By the evening of the 8th, there were only a few light snow showers left over some eastern target areas bringing only about 0.1 inch of total precipitation, and all sites were been turned off by 1700 MST.

After nearly two weeks of no seedable storm systems for northern Utah, a very deep trough was observed on February 21st dropping from the coast/interior of Canada into the northwestern United States, which brought a band of deep moisture and widespread light precipitation over northern Utah during the mid-morning. The 700 mb level experienced fairly strong west-southwesterly winds of roughly 40 knots and temperatures near – 6° C, and the valley remained decently mixed out with temperatures falling in the 30s at lower elevations and limited liquid water available per the weather radar vertical profile data. Around 1200 MST, temperatures cooled and winds shifted to west-northwesterly allowing seeding operations to begin at some northwestern Box Elder sites, and within the next 2-3 hours, almost all CNG sites. Later in the evening, a broad band of SW-NW-oriented snowfall developed and remained focused on western/central Utah, and seeding operations were stopped for sites along I-15 because of northerly-shifting winds. Cache County CNG sites continued running throughout the night, but on the morning of February 22nd, 700 mb temperatures had dropped to around -15° C with little to no supercooled liquid water (SLW) available, and all CNG sites were turned off around 0900 MST. The storm produced a total of 0.7-1.7 inches of precipitation.

The last week of February saw stormy low-pressure conditions, with an extensive trough observed in the northeastern pacific on the 26th, and an associated cold front pushing inland during the late morning/early afternoon. Snowfall gradually increased throughout the day, and seeding operations began around 1900 MST due to favorable wind patterns, increasing SLW availability, and 700 mb temperatures near -8 to -10° C. Light and mostly orographic precipitation was seen in southwesterly flow the morning of the 27th, and more CNG sites were activated that afternoon. By 1900 MST, a cold frontal boundary was observed crossing over the area, causing winds to shift mostly westerly (northwesterly briefly), so CNG sites continued to run overnight (February 27-28), accompanied by convection and lightning over northern Utah. The morning of the 28th saw a little more orographic-type snowfall which gradually tapered off throughout the afternoon, with all seeding operations ending by around 1400 MST on February 28th.

Figure 4.7 shows precipitation for February of 2023 as a percentage of the median.



Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

Figure 4.7 **February 2023 precipitation, percent of normal**

March 2023

A weak storm system was observed over northern Utah on March 3rd which brought light snowfall and cold 700 mb temperatures around -14° C to the area during mid to late morning. Limited liquid water and cloud tops near 15,000 feet dominated by the ice process made any effective seeding difficult during that time, but moderate snowfall and weak convective activity did finally develop due to daytime heating and resulted in activation of a few CNG sites around 1045 MST. The sites ran for a few hours, but around

1400, snow showers heavily tapered off after fairly minimal accumulation of precipitation, and all seeding operations ended by 1430 MST. Precipitation amounts were light, mostly 0.1 – 0.2 inches.

The next day on March 4th, a cavernous low-pressure trough was observed centered off the Pacific Northwest coast. During the mid-afternoon, satellite images showed multiple low centers offshore, and mostly high clouds over northern Utah with light snowfall mainly aloft. The 700 mb temperatures were near -8 to -10° C with south-southwesterly flow, but liquid water was limited throughout the day and overnight, with widespread snowfall originating from a higher cloud deck. Valley temperatures in parts of far northern Utah during mid-afternoon were in the 20s, and surface stability made seeding operations difficult at the time. However, GFS and other forecast models showed pre-frontal activity from cold advection above 600 mb and warm advection below, generating a small amount of convective energy (CAPE). Later that evening around 1700 MST, significant snowfall and southerly winds began over northern Utah, and a few south-side CNG sites at higher elevations were activated. The morning of the 5th brought about partial clearing of the storm, and all seeding operations ended by 1100 MST. Reports and data suggested about 6-12'' of new snow that night around most eastern target areas, and the large trough remained stationed near the northwestern U.S. with its center residing off the northern coast of California. Precipitation amounts were generally about 0.7 – 1.3 inches of water equivalent.

Quickly following the previous storm period, another cold frontal boundary made its way across the northern Utah area on the evening of March 5, causing 700 mb temperatures to fall around -12° C and winds to shift from south-southwesterly to west-northwesterly. Liquid water content was still limited by cold temperatures and a lack of lower-level moisture, but as the afternoon progressed into the evening, slight embedded convection helped generate areas of seedable liquid water clouds, and some CNG sites were activated around 1500 MST to accommodate favorable southwesterly flow. Most sites were turned off just before midnight, but a few ran until the morning of the 6th, at which point the snowfall had mostly ended, leaving 0.2-0.6 inches of recorded precipitation.

The next seedable storm moved through northern Utah on March 15th, but was rather small. The early morning saw cold temperatures and some scattered showers in west-northwesterly flow, along with a cold advection pattern as 700 mb temperatures fell to around -10° C. The National Weather Service had issued flood advisories to the north on the Idaho-side of the border due to rain and snowmelt, but no flood highlights were issued on the Utah side, and low-level winds remained mostly southerly during the morning. Surface and dew point temperatures both remained above freezing at lower elevations such as Cache Valley a little later in the morning, and by 0930 MST, conditions became somewhat marginal for seeding. Only a few showers were forecasted at this point, and liquid water was slightly limited, but a few CNG sites in eastern portions of the target area were activated around 1000 MST where conditions were more favorable. A few hours later, snow showers had ended and left only partly cloudy skies in the afternoon, and all seeding operations ended by 1300 MST.

A negatively tilted, mostly occluded trough moved into the northern Utah area during the early/mid-afternoon on March 19th, bringing with it a frontal band of light to briefly moderate precipitation and generally weak warm advection in south-southwesterly flow. The 700 mb sustained temperatures near -6° C for much of the day, and the valleys experienced a mixture of rain (I-15 area) and snow (Cache Valley). This was a start, but conditions were not suitable for seeding until the morning of March 20th, when ample moisture from another system moving across the great basin barreled in, and cooling aloft lead to convective-type precipitation. 700 mb temperatures dropped between -7 and -9° C, and CNG sites which favored southwesterly flow were activated around 1000 MST. In the early afternoon, a more significant band of precipitation, associated with mid-upper-level rotation over the west desert, crawled across northern Utah. Over the next few hours into the late evening, two different snow squalls made their way through northern Utah as well, and some eastern target areas continued to receive light convective/orographic snow showers overnight associated with a shortwave trough near the Idaho border. A few CNG sites continued to seed these systems overnight, but all operations ended around 0600 MST on March 21st. Precipitation totals were mostly between 0.5 – 1.0 inches of water content.

The rest of the day on the 21st stayed mostly dry, with the exception of some weak advection associated with light precipitation from a high cloud deck late that evening, but another major storm system was observed developing near the California coast. The morning of March 22nd saw areas of snowfall with cooling aloft as 700 mb temperatures dropped from -7 to around -9° C. A low-pressure center with generally southwesterly winds (though variable at lower-levels) was seen developing just over northern Utah, however many valleys, including Cache, remained stable throughout the morning with light winds favoring a northerly direction. Despite the valley stability, CNG sites were activated around 1200 MST on the premises that conditions would improve. A few hours later, a large area of light to moderate snowfall developed around a center of circulation over northern Utah and low-level winds became southerly (south-southwesterly aloft), improving valley mixing and allowing continued usage of CNG sites on the southern side of eastern target areas. By the late evening, low-level moisture was still abundant, and orographic-type snowfall continued overnight. These showers slowly tapered off in a light westerly flow pattern with limited moisture by the morning of the 23rd, so seeding operations ended by 0800. Precipitation totals were quite variable in this event, ranging from about 0.2 – 1.0 inches.

The last seedable storm for the northern Utah target area came one day later on March 24th. A decently energetic cold front moved across the area and brought somewhat convective and disorganized snow showers overnight, and the morning of the 24th saw a north-south band of light/moderate snowfall with 700 mb temperatures around -10° C. Seeding operations at sites favoring a westerly flow pattern began around 0800 MST. In the late afternoon, main bands had moved through northern Utah leaving between about 1 to 2 inches of precipitation in most areas during the event, and snow showers continuing mainly in the southern half. By the late evening, convective and orographic showers had continued with west-northwesterly flow and ideal wind speeds had helped enhance storm development. This, however, slowed down due to a loss of heating and moisture, which developed into an icy environment not ideal for the continuation of cloud seeding.

Following the March 24 event there was a discussion regarding the extreme amounts of low-to-mid elevation snowpack and flooding concerns which had developed. Despite the higher elevation CNG sites not having quite reached the technical suspension criteria, they appeared to be under-representative of the overall snowpack situation and flood risk due to the fact that the lower elevation sites (with the most extreme snowpack values) are not considered for these criteria. Based on this, it was agreed to suspend operations for the remaining week of the program.

Figure 4.8 shows March 2023 precipitation as a percentage of the historical median values, with nearly all of northern Utah being over 200% of the March median.

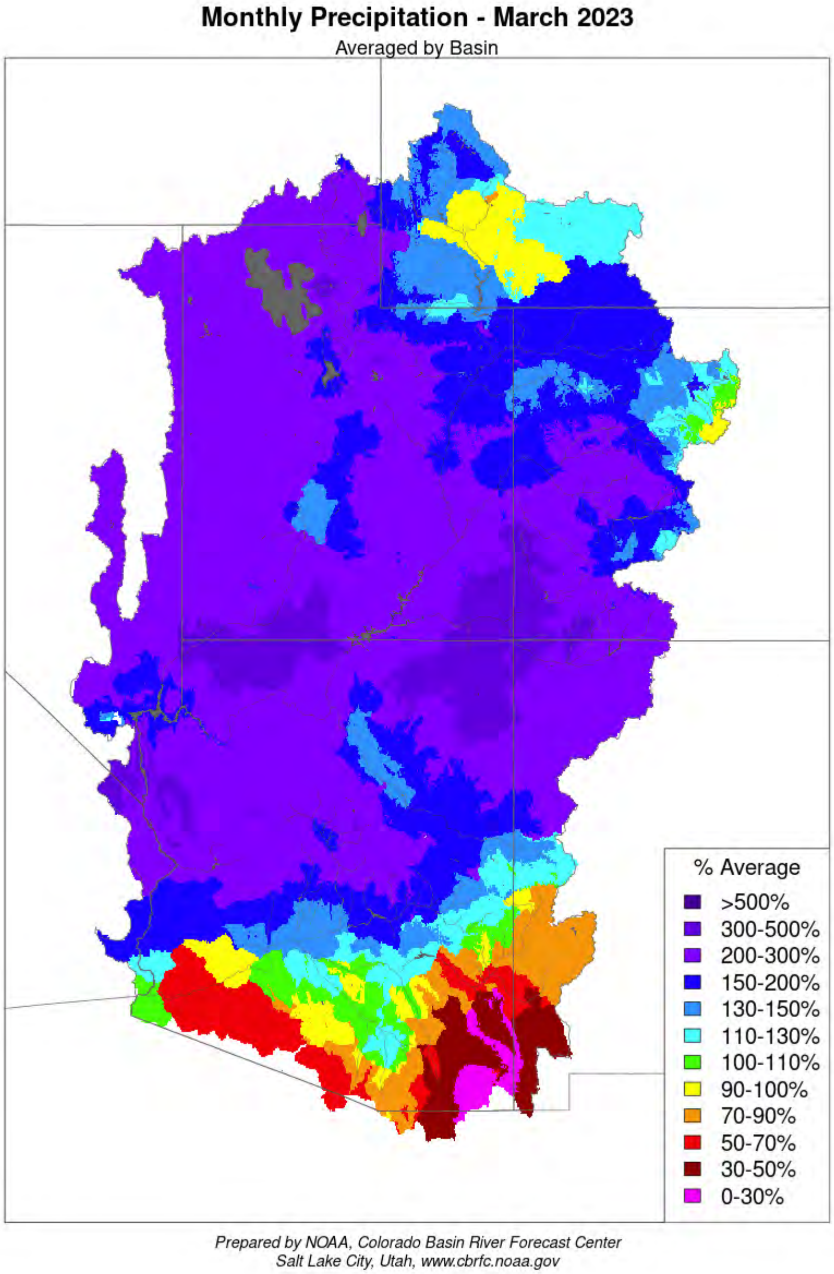


Figure 4.8 **March 2023 precipitation, percent of normal**

5.0 ASSESSMENT OF SEEDING EFFECTS

5.1 Background

Determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program is often a rather difficult task, especially when considering single-season results. The primary reason for this difficulty stems from the large natural variability in the amounts of precipitation that occur in a given region. The ability to detect seeding effects is a function of the size of the seeding increase relative to the natural variability in the precipitation pattern. Larger seeding effects can be detected more readily and with a smaller number of seeded cases than are required to detect smaller increases.

Historically in weather modification, the most significant seeding results have been observed in wintertime seeding programs for snowpack augmentation in mountainous areas. The apparent increases due to seeding are generally less than 20% for individual seasons and in the range of 5-15% for the long-term average. This section of the report summarizes statistical evaluations of the effects of the cloud seeding on the precipitation and snowpack within the higher elevations of this program's targeted areas. When expressed as percentages, the increases may not initially appear to be particularly high. However, when considering that these increases are area-wide averages covering thousands of square miles, the volume of the increased runoff can be very significant.

NAWC has utilized a commonly employed evaluation technique, referred to as a target and control evaluation. This method evaluates the effects of seeding on a variable that would be affected by seeding, such as precipitation or snow. Records of the variable to be evaluated are acquired for an historical (unseeded) period of sufficient duration, 20 years or more if possible. These records are partitioned into those that lie within the designated seeded target area of the project and those in a nearby control area. Ideally the control area consists of sites well-correlated with the target area sites, but which would be unaffected by the seeding. All the historical data, for example, 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 the most likely 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 actually occurred.

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 the effects of the seeding activities at times. This can result in an underestimate of the seeding effect when using such control sites. For precipitation and snowpack assessments, correlations of 0.90 or better are considered excellent and correlations around 0.85 are good. A correlation of 0.90 indicates that over 80 percent of the variance (random variability) in the historical data set is explained by the regression equation. Correlations less than about 0.80 can still be acceptable, but it would likely take much longer (many more years of comparison for both historical data and seeded periods) to attach any statistical significance to the apparent seeding results.

5.2 General Considerations in the Development of Target/Control Evaluations

With the establishment of the Natural Resources Conservation Service's (NRCS) Snow Telemetry (SNOTEL) automated data acquisition system in the late 1970's, access to precipitation and snow water equivalent data in mountainous locations became routine. Before the automated system was developed, these data had to be acquired by having NRCS personnel visit the site to make measurements, which is still done at some sites. Precipitation and snowpack data used in the analysis were obtained from the NRCS website. The current season NRCS data are considered provisional and subject to quality control analysis. Figure 5.1 is a photo of a SNOTEL site with the major components labeled.

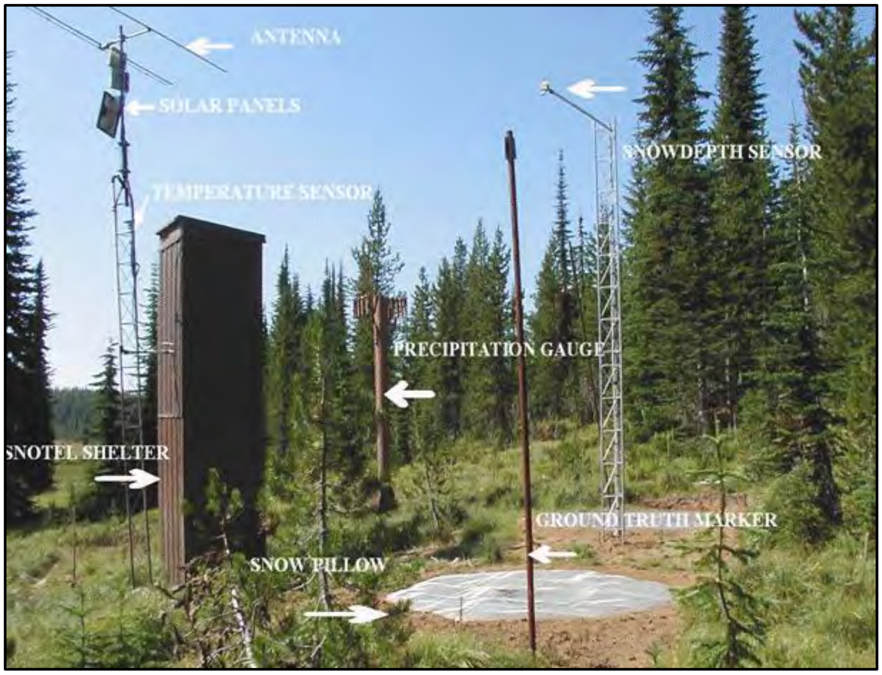


Figure 5.1 **SNOTEL site photo**

There are multiple cloud seeding programs conducted in the State of Utah. Consequently, potential control areas that are unaffected by cloud seeding are somewhat limited. This is complicated by the fact that the best correlated control sites are generally those closest to the target area, and most measurement sites in this part of the state have been subjected to likely impacts by the numerous historical and current seeding programs. This renders such sites of questionable value for use as control sites. The potential effects of other cloud seeding projects beyond (downwind of) their intended target areas are a consideration, especially when selecting control sites. Some weather modification research has indicated that the precipitation can be affected in areas substantially downwind of the intended target areas. Analyses of some of seeding programs has indicated increases in precipitation in these downwind areas out to distances of 50-100 miles. Thus, control sites for evaluation of the northern Utah seeding program are located in areas that are not expected to be significantly affected by any current or historical seeding operations.

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

Another consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control site may be rejected due to poor data quality, which usually manifests itself in terms of missing data. A site would be excluded if it has significant amounts of missing data. If a significant measurement site move is indicated in the station records, for example more than a mile or a change in elevation of a least a few hundred feet, this may also be a factor. The double-mass plot, an engineering tool, will indicate any systematic changes in relationships between the two stations. If changes shown as inflections in the slope of the line connecting the points are significant, a site(s) may be excluded from further consideration.

Using the target-control comparison described above, regression equations were developed whereby the amount of precipitation or snowpack observed in the unseeded (control) area was used to estimate the amount of natural precipitation in the seeded (target) area. This estimated value is the amount of precipitation or snowpack that would be expected in the target area without seeding. The difference between the estimated amount and the observed amount in the target area (during a seeded season) is the excess, which may be the result of the seeding. Statistical tests have shown that such increases have very little statistical significance for an individual season, and usually fall within one standard deviation of the natural variability. However, an excess obtained by averaging the results of multiple seeded seasons is much more meaningful.

5.3 Evaluation of Precipitation and Snowpack in the Target Areas

Precipitation data used in these analyses were obtained from the NRCS and/or from the National Climatic Data Center and represent the official published records of those organizations. Similar snow water equivalent records used in the snowpack analysis were also obtained from the NRCS. The current season NRCS data are considered provisional at the time this report is being prepared.

Precipitation and snowpack data evaluations for the 2022-2023 water year are included in the report sections covering seasonal data, but will be excluded from the calculation of long-term values and graphs due to very anomalous weather patterns this season. The precipitation and snowpack data types were widely variable in the results produced in the target/control analysis, in part due to how control site areas differed from the target areas in the observed weather patterns. Also, consistently cold temperatures led to anomalous geographic distributions of snowpack, with the lower and mid elevations exceeding all snowpack records in many areas. Higher elevation sites, while having far above normal snowpack, were less extreme in comparison to historical data.

5.3.1 Precipitation Analysis

Precipitation measurements are available from several locations within the mountain watersheds of the Eastern Box Elder and Cache County portions of the target area. In northwestern Box Elder County, precipitation sites with sufficient historical records are not available, so no precipitation analysis has been conducted for that area. However, snowpack analyses from snowcourse and SNOTEL sites in the northwestern Box Elder target are included in the analyses.

5.3.1.1 Target Area Gauge Sites

The selected target sites extend southward from near the Idaho/Utah border (west of Bear Lake), along the crest of the Wasatch mountains between Cache and Rich Counties, to the southeast corner of Cache County, near Monte Cristo R.S.). The precipitation sites extend westward along the mountains between Weber and Cache Counties to the Ben Lomond Peak area. The latter is in the Weber/Ogden watershed, but is very likely affected by the seeding generators in southeastern Box Elder County and should represent seeding affecting the Little Bear River and Davenport Creek drainages. The seven precipitation gauge sites that constitute the target area are shown in Figure 5.2. These sites range in elevation from 6,000 to 8,960 feet above mean sea level (MSL). The average elevation of the target sites is 7,744 feet above MSL. The names, locations, and elevations of the sites are listed in Table 5-1.

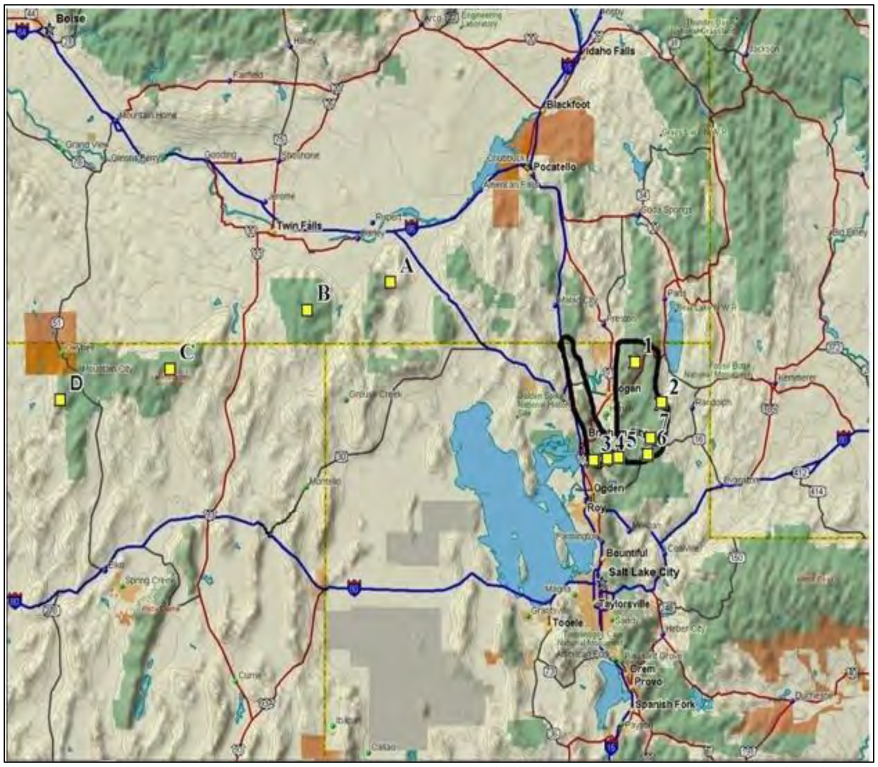


Figure 5.2 Precipitation gauge sites used in evaluation, eastern Box Elder and Cache Counties, with site data in Table 4-1. The target area is outlined in black. The target sites are numbered; the control sites have letter ID's.

Table 5-1
Target and Control Precipitation Gauge Locations, Eastern Box Elder/Cache County Evaluation

ID	Site Name	Site No.	Elev. (Ft)	Lat. (N)	Long. (W)
Control Sites					
A	Howell Canyon, ID	I13G01	7,980	42° 19'	113° 32'
B	Bostetter RS, ID	I14G01	7,500	42° 10'	114° 11'
C	Pole Creek RS, NV	N15H14	8,330	41° 52'	115° 15'
D	Fawn Creek #2, NV	N16H10	7,050	41° 49'	116° 06'
Target Sites					
1	Tony Grove Lake	U11H36	8,400	41° 54'	111° 38'
2	Bug Lake	U11H37	7,950	41° 41'	111° 25'
3	Ben Lomond Peak	U11H08	8,000	41° 22'	111° 57'
4	Ben Lomond Trail	U11H30	6,000	41° 23'	111° 55'
5	Little Bear Upper	U11H25	6,550	41° 24'	111° 49'
6	Dry Bread Pond	U11H55	8,350	41° 25'	111° 32'
7	Monte Cristo	U11H57	8,960	41° 28'	111° 30'

5.3.1.2 Control Area Gauge Sites

Widespread seeding activity in Utah has compromised, if not eliminated, most of the nearby high-elevation sites along the Wasatch Mountains as possible control sites. To further complicate the matter, the number of established storage gauge/snow course sites has been reduced, with some eliminated as SNOTEL sites were developed to replace them. In addition, the cooperative observer sites, which are managed by the National Weather Service, have also had reductions. All target/control sites used in last year’s analyses remain active and were used again this season.

The program in northern Utah has been conducted for the period of December – March for most of its history. For this reason, the December – March period is used in the precipitation target/control analyses. The sites used for these analyses are the same as those used previously. The average elevation for the four control area precipitation gauges is 7,715 feet MSL. They are shown in Figure 5.2, with their locations and elevations provided in Table 5-1.

The database utilized for the mountain target area sites in the evaluations was developed from NRCS SNOTEL and snow course data. Some estimation of monthly precipitation totals was necessary before about 1988, since after this time NRCS began replacing storage gauge sites (which required a manual reading) with automated SNOTEL sites. Since then, reliable monthly readings have been available from all the SNOTEL sites.

5.3.1.3 Regression Equation Development

Monthly precipitation values were totaled at each gauge in the control and target areas for the December-March period in each of the historical, non-seeded water years of 1970 through 1988 (19 seasons), and averages for each group were obtained. The predictor equation was developed from these data for the December - March period:

$$Y_C = 0.33 + 1.27(X_0) \tag{1}$$

where Y_C is the calculated average target precipitation (inches) and X_0 is the 4-station Nevada/Utah control average observed precipitation (inches) for the December-March period.

The four-site control has a fairly strong correlation with the target area gauge sites for the 19 historical years (1970-88 water years) with a correlation coefficient of 0.91. This correlation coefficient provided a variance (r^2) of approximately 0.82, indicating that 82 percent of the variance in the historical data set could be explained by the regression equation used to predict the precipitation in the seeded years.

A multiple linear regression analysis is also included among the analyses. This technique has also been used in the evaluation of some of the other cloud seeding programs in Utah and is similar to the linear regression technique, with the same data sets used in both. The multiple linear technique relates each control site individually (or, in some cases, groups of control sites) to the average target area precipitation whereas the simple linear regression technique relates the average of the control sites to the average of the target sites. The multiple linear regression method was considered since it typically provides a higher correlation between the control and target areas. That was the case in Northern Utah where an r value of 0.94 was obtained using the four available control sites. The resulting equation is:

$$Y_C = 1.24 + 0.57(X_1) - 0.21(X_2) + 0.13(X_3) + 0.75(X_4) \tag{2}$$

where Y_C is the calculated average target precipitation (inches), X_1 is Howell Canyon SNOTEL (ID), X_2 is Bostetter R.S. (ID), X_3 is Fawn Creek #2 (NV), and X_4 is Pole Creek (NV).

5.3.1.4 Linear Regression Evaluation Results

When the observed average control precipitation of 16.50 inches for the December 2022 through March 2023 period was inserted in equation (1), the most probable average target area natural precipitation was calculated to be 21.25 inches using the linear regression technique. The average observed precipitation for the seven gauges in the target group was 33.53 inches.

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

$$SE = R = Y_0 / Y_C \qquad (3)$$

where Y_0 is the target area average observed precipitation (inches) and Y_C is the target area average calculated (predicted) precipitation (in inches).

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

$$SE = [(Y_0 - Y_C) / Y_C] *100 \qquad (4)$$

From equation (3), the ratio of the average observed precipitation to the average calculated precipitation in the target area during the December – March period was 1.58. As previously noted, individual year ratios in the target/control analysis are not very meaningful, because they can be greatly affected by variations in weather patterns affecting the target and control sites. It is important to note that the season-to-season variability in the weather primarily affects the mathematical results obtained in the target/control analysis, to a much greater degree than the actual effectiveness of the cloud seeding which theoretically should be somewhat consistent on a percentage effect basis from year to year.

When the data, using the four-site control group, are combined for the 34 seeded December-March periods (1989-2023 water years, excluding water years 2023 and 2017 due to seeding suspensions and anomalous precipitation patterns as described above and in the 2017 report), **the indicated average increase in the eastern Box Elder/Cache County target area is 5%. The seasonal (December-March) difference between the observed and calculated precipitation is an area-wide average of 0.9 inches more than predicted during the seeded periods.** Appendix C shows additional information for all the historical and seeded years in the regression analyses. There was a correction to the precipitation data at one target site (Ben Lomond Peak) for the past season, resulting in a slight change to the long-term results despite the exclusion of the 2023 data.

There are several types of plots that can be used to illustrate the mathematical difference between the seeded and non-seeded years. Figure 5.3 is a plot of the ranked ratios of observed to calculated precipitation in the Eastern Box Elder/Cache County target area for all the water years (December - March period) used in the evaluation. This consists of a total of 52 water years, with the 19 water years from 1970 through 1988 representing the historical (unseeded) years and the remaining 33 years (1989 – 2022, excluding 2017) being the seeded years. The reader should remember that in developing the regression equation the mean of the ratio of all the historical years is 1.0, and therefore (by definition) approximately one-half of the historical years (denoted by the white bars) will be below 1.0. The ratios are plotted in ranked ascending order from left to right in the figure. It is evident that the highest ratios generally occur in the seeded years (black bars), which dominate the right side of the plot. Figure 5.4 is a scatterplot comparing the seeded and non-seeded seasons, with the regression lines shown for both the seeded and non-seeded years' data. This illustrates the mathematical differences between the seeded and non-seeded data sets, as well as the amount of spread for individual seasons.

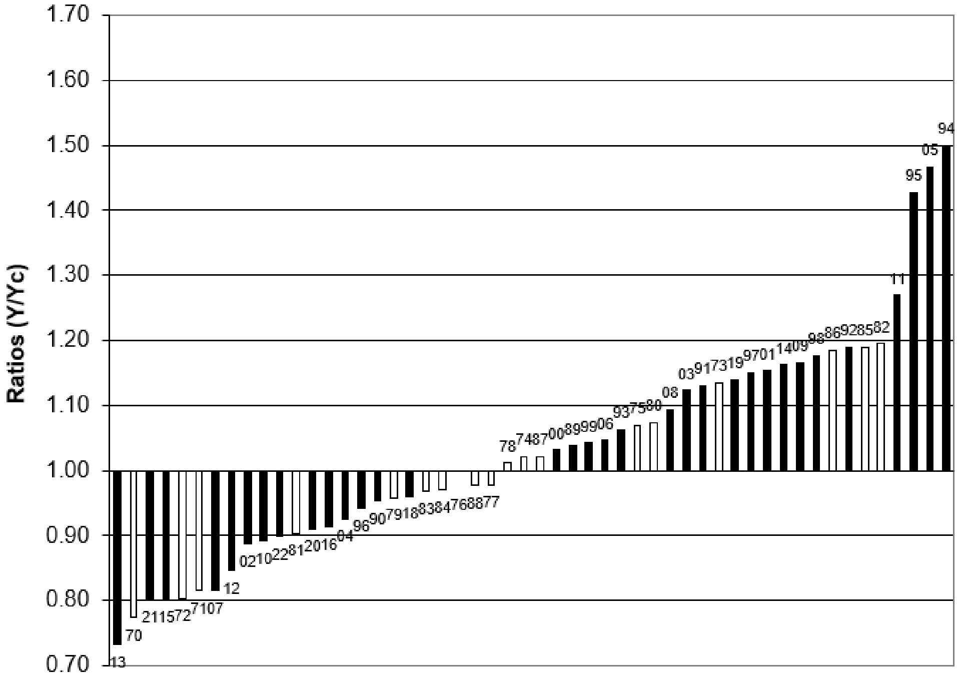


Figure 5.3 **Calculated ratios for 1970-2022 December – March precipitation, Eastern Box Elder/Cache County Program, using the linear regression technique; White bars represent the historical, unseeded years and black bars the seeded years.**

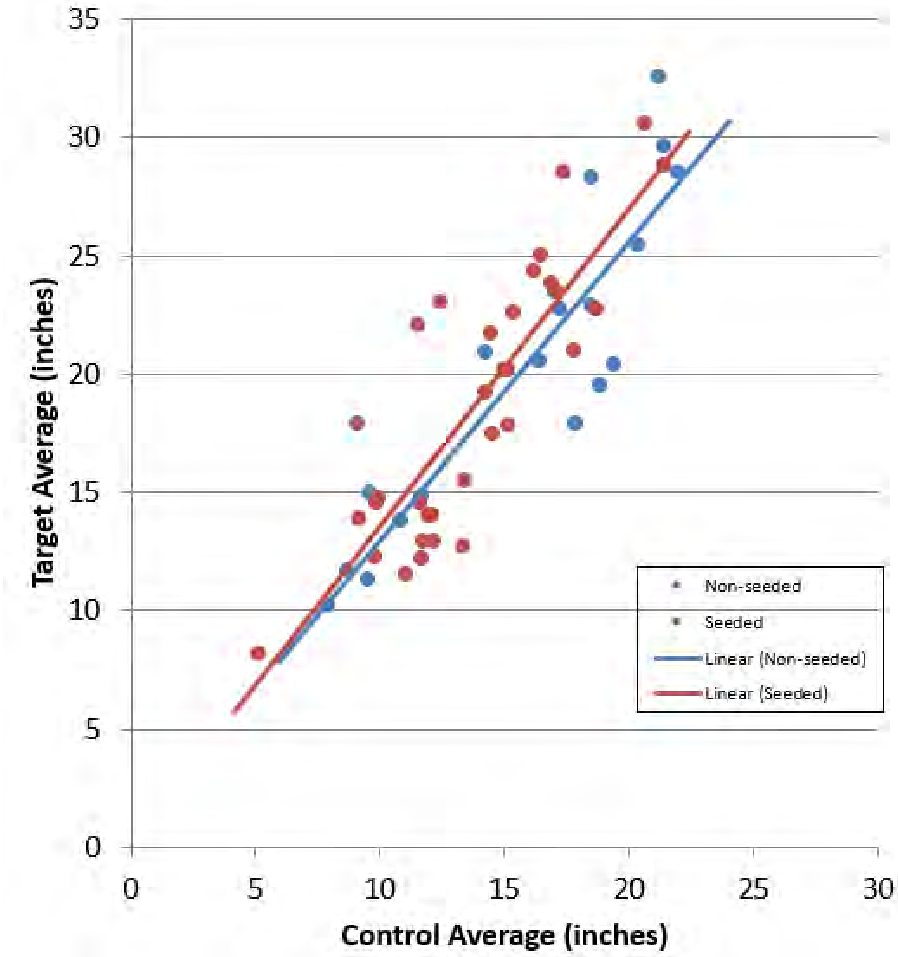


Figure 5.4 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for eastern Box Elder and Cache County precipitation linear regression

Figure 5.5 is a double mass plot, an engineering tool designed to display data in a visual format in which it can readily be seen if there has been a change in the relationship between two measurements or variables. NAWC has applied this technique to the northern Utah cloud seeding program. As noted earlier in this report, the northwestern Box Elder County target area has only a snowpack data regression analysis. Target and control area-average seasonal values for both the historical (not-seeded) and the seeded periods are plotted on the figures. The plotted values are cumulative, meaning that each new season is added to the sum of all the previous seasons. In each figure, a line has been drawn through the points during the not-seeded base period. The plots show stable linear relationships prior to the beginning of cloud seeding. For comparison with the seeded period, the line describing the not-seeded period is extended at a constant slope through the seeded period.

The double-mass plot (Figure 5.5) shows a distinct change in the relationship between the target and control areas (a sustained change in the slope of the line representing the seeded seasons) that begins at approximately the same time as the start of the cloud seeding program in 1989. **Beginning at/near this time the plots in each case show greater precipitation and more April 1 snowpack water content in the target area compared to the control area. NAWC believes that this is evidence of a consistent, positive seeding effect.** A separate line could be drawn through the data points since about 1989. Such a line would have a rather constant slope, departing from the slope of the line describing the non-seeded base period.

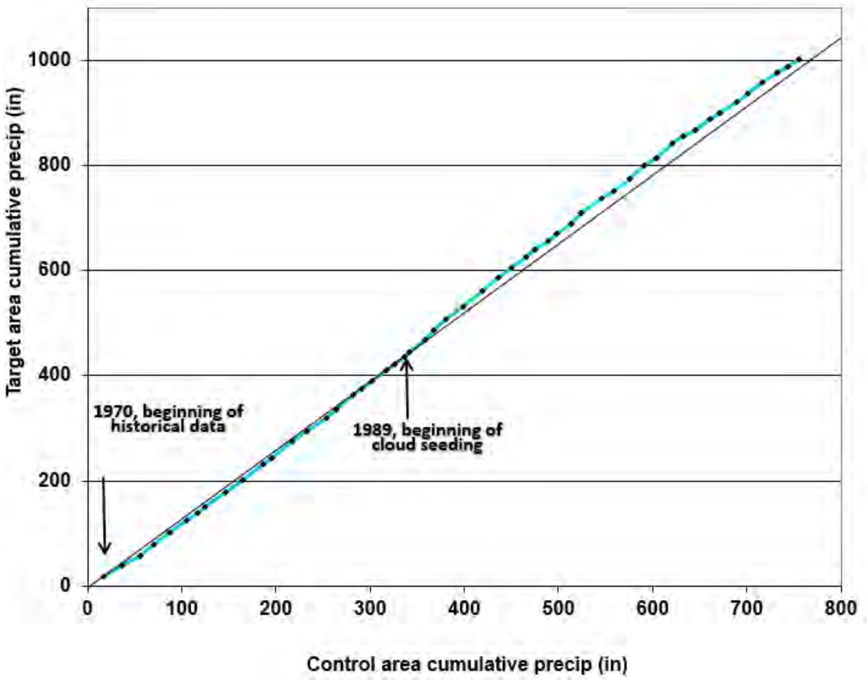


Figure 5.5 **Double mass plot showing cumulative Dec-Mar <u>precipitation</u> for eastern Box Elder and Cache County target and control areas, water years 1970-2022.**

5.3.1.5 Multiple Linear Regression Evaluation Results

The results of the precipitation multiple linear regression as a whole are similar to those for the linear regression, but again, the 2022-23 water year was quite extreme, therefore some multiple linear regression values are quite different from the linear regression. The resulting multiple linear regression ratio for this season is 1.51 with a ratio of 1.06 for the 33 previous seeded seasons of data, suggesting an average of 1.0 inches of increased water per season (which is similar to that of the corresponding linear regression). Additional details are contained in Appendix B.

5.3.2 Snowpack Analysis

The water content within the snowpack or snow water equivalent (SWE) is important since, after consideration of antecedent soil moisture conditions, it ultimately determines how much water will be available to replenish the water supply when the snowmelt occurs. Hydrologists routinely use snow water content to generate forecasts of streamflow during the spring and early summer months.

As with the precipitation storage gauge and SNOTEL precipitation gauge networks, the State of Utah also has an excellent snow course and SNOTEL snow pillow reporting system. Many of the same stations are available for snow water measurements as those for precipitation measurements. Consequently, snow water measurements were utilized to conduct an additional evaluation of potential seeding effects.

There are some potential pitfalls with SWE data that 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. This can lead to a disparity between precipitation totals, which include all precipitation that falls, and snowpack water content, which measures only the water contained in the snowpack at the time of measurement. Also, warm periods can occur between snowstorms. If a significant warm period occurs, some of the precipitation that fell as snow may melt. Thus, snowpack water content may be reduced, and may not reflect the total snowfall for the season. This can also lead to a disparity between snow water content at higher elevations (where less snow will melt in warm weather) and that at lower elevations.

Another variable that can affect the results of the snowpack evaluation, in the context of manual snow course sites, is the date on which the snowpack measurement was made. Any manual snow course measurements are usually made <u>near</u> the end of a month and, since the vast majority of the snowpack sites are automated SNOTEL sites with daily data, timing is generally not a major issue. However, prior to SNOTEL, and at those sites where snow courses are still measured by visiting the site, the measurement is recorded on the day it was made. In some cases, because of scheduling issues or stormy weather, these measurements can be made as much as several days before or after the end of the month. This variability can complicate the relationship between the sites in the control and target groups.

Most of the snowpack data used in this analysis are from sites that were originally snow course sites, but were converted to SNOTEL sites after approximately 1980 (some much later than others). The data set that was utilized in some prior season evaluations contained both snow course and SNOTEL data for these sites. However, it was recognized that this could present a problem because of potential differences between the snow course and SNOTEL measurement techniques. The NRCS recognized this potential problem, and obtained concurrent data at the newly established SNOTEL sites using both (collocated) measurement techniques for an overlap period of approximately 10 years in duration. The NRCS then developed mathematical relations that converted the previous monthly snow course measurements to estimated values, as if the SNOTEL measurements had been available at these sites. The resulting estimated data at some sites were very similar to the original snow course data while there were differences of 10-15% at a number of the sites. Some sites today continue as manually observed snow course sites. The use of data from these sites continues without any changes to the data type.

5.3.2.1 Target Area Snowpack Sites

The eastern Box Elder/Cache County target group consists of seven sites. These sites are the same sites used in previous evaluations. The sites are shown in Figure 5.6, and names and locations are listed in Table 5-2. The average elevation of the target area sites is 7,760 feet MSL. A snowpack evaluation was also conducted for northwestern Box Elder County, using two available snow course/SNOTEL sites. Figure 5.6 depicts these site locations as well, and Table 5-2 lists pertinent site data.

5.3.2.2 Control Area Snowpack Sites

Figure 5.6 shows the locations of the eastern Box Elder/Cache County control area snowpack sites. The site names and locations of the five control sites are listed in Table 5-2. The average elevation of these sites is 7,298 feet MSL. The same control set used for eastern Box Elder and Cache counties is also used to evaluate the northwestern Box Elder County portion of the program.

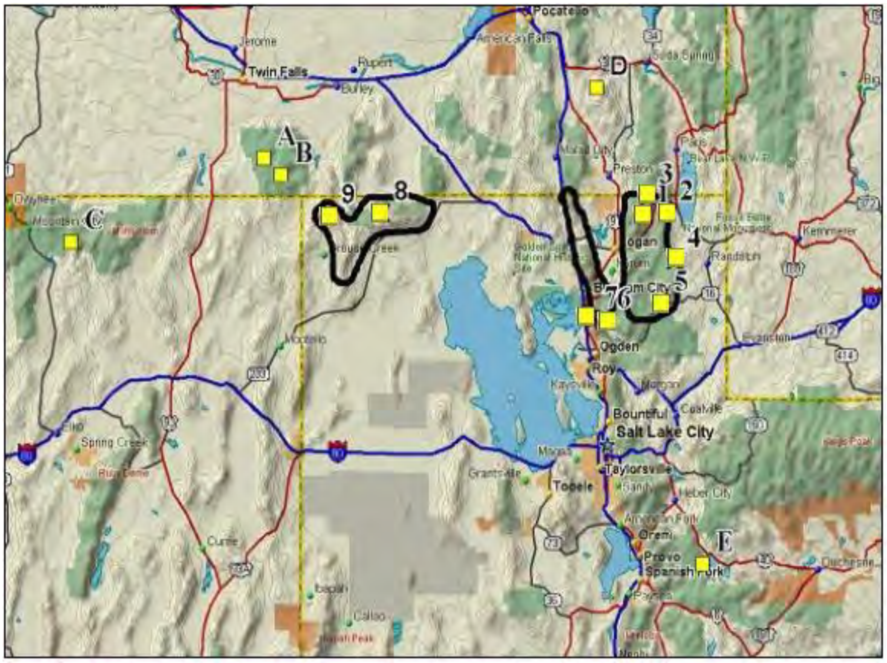


Figure 5.6 Target and control sites used in eastern Box Elder/Cache County snowpack evaluation, with site data shown in Table 4-2. The target areas are outlined in black. The target sites are numbered; the control sites have letter ID's.

Table 5-2
Snowpack Control and Target Measurement Sites

ID	Site Name	Site Number	Elevation (Ft)	Latitude	Longitude (W)
Control (for both areas)					
A	Magic Mountain, ID	14G02S	6,880	42° 11'	114° 18'
B	Badger Gulch, ID	14G03S	6,660	42° 06'	114° 11'
C	Big Bend, NV	15H04S	6,700	41° 46'	115° 41'
D	Sedgwick Peak, ID	11G30S	7,850	42° 32'	111° 58'
E	Strawberry Divide, UT	11J08S	8,400	40° 11'	111° 13'
Eastern Box Elder/Cache County Target					
1	Tony Grove Lake, UT	11H36	8,400	41° 54'	111° 38'
2	Garden City Summit, UT	11H07	7,600	41° 55'	111° 28'
3	Klondike Narrows, UT	11H01	7,400	41° 58'	111° 36'
4	Bug Lake, UT	11H37	7,950	41° 41'	111° 25'
5	Monte Cristo, UT	11H57	8,960	41° 28'	111° 30'
6	Ben Lomond Trail, UT	11H30	6,000	41° 23'	111° 55'
7	Ben Lomond Pk., UT	11H08	8,000	41° 23'	111° 57'
Northwestern Box Elder County Target					
8	George Creek, UT	13H05	8,840'	41°54'	113°29'
9	Vipont, UT	13H03	7,670'	41°54'	113°51'

5.3.2.3 Regression Equation Development

The procedure was essentially the same as was done for the precipitation evaluation, i.e., control and target area stations were selected and average values for each were determined from the historical snowpack data. The same 19-year historical period (1970-88 water years) that was used in the precipitation evaluation was also used for the snowpack evaluation. The snowpack simple linear regression equation developed for Eastern Box Elder/Cache Counties, using historical SNOTEL and estimated SNOTEL April 1st snow water content data, was:

$$Y_C = 1.47 + 1.44(X_O) \qquad (5)$$

where Y_C is the calculated average target area snowpack based on X_O (the observed average control area snowpack). The correlation coefficient r was 0.91, with an r^2 value of 0.83.

For northwestern Box Elder County, the equation is:

$$Y_C = 2.15 + 0.95(X_O) \qquad (6)$$

The correlation coefficient (r) was 0.91, with an r^2 value of 0.83.

As in the precipitation evaluation, multiple linear regression analyses were also performed on the snowpack data. In some cases, it has been found that averaging groups of control sites for use in the multiple linear regression analysis can yield a mathematically superior prediction of target area precipitation compared to using each control site individually. This is typically the case when there are more than about 4 or 5 control sites, and/or when some of the control sites are in close proximity to each other. The result of such grouping of control sites can be observed mathematically in the form of decreased year-to-year variability in the observed/predicted target area ratios which are obtained. The objective is to minimize the level of background “noise” (e.g., seasonal variations in natural precipitation patterns between control and target areas) to provide as accurate a prediction as possible of the “natural” (non-seeded) precipitation in the target area during each seeded season. The April 1 snowpack multiple regression equation that was developed for Eastern Box Elder/Cache Counties (using each control site individually) is:

$$Y_C = -5.24 + 0.06(X_1) + 0.39(X_2) – 0.56(X_3) + 0.62(X_4) + 0.80(X_5) \qquad (7a)$$

where $X_1 \ldots X_5$ are Magic Mountain (ID), Badger Gulch (ID), Big Bend (NV), Sedgewick Peak (ID), and Strawberry Divide (UT), respectively. The r value obtained with this analysis was 0.97, as compared to 0.91 from the linear regression equation.

When two groups of control sites were averaged for use with the multiple regression technique, the number of independent control variables was reduced from five to two. In this case, an average of the three Idaho sites (Magic Mountain, Badger Gulch, and Sedgewick Peak) constitutes a northern group, and the remaining two (Big Bend, NV and Strawberry Divide, UT) a southern group. The resulting equation is:

$Y_C = 1.78 + 0.78(X_1) + 0.67(X_2)$ (7b)

where X_1 is an average of the Idaho sites and X_2 an average of the two Nevada/Utah control sites. The R-value for equation 7b is 0.91, very similar to that for the linear regression equation.

The multiple linear regression equation that was developed for Northwestern Box Elder County (using each control site individually) is:

$Y_C = 2.09 + 0.36(X_1) + 0.43(X_2) – 0.18(X_3) + 0.13(X_4) + 0.33(X_5)$ (8a)

where $X_1....X_5$ are Magic Mountain (ID), Badger Gulch (ID), Big Bend (NV), Sedgewick Peak (ID), and Strawberry Divide (UT), respectively. The r value obtained with this analysis was 0.94 as compared to 0.91 from the linear regression equation.

$Y_C = 2.78 + 0.72(X_1) + 0.25(X_2)$ (8b)

where X_1 is an average of the Idaho sites and X_2 an average of the two Nevada/Utah control sites. The r value obtained with this analysis was 0.91, again very similar to that of the linear regression equation. However (and this is particularly true of the Box Elder County snowpack evaluation), the multiple regression equations with two groups of control sites (e.g. 7b and 8b) yield less year to year variability of the observed/predicted ratios than do the original forms of the multiple regression (7a and 8a). This implies greater mathematical stability and likely more accurate indications of true seeding effects.

5.3.2.4 Results of Linear Regression Snowpack Evaluation

The April 1, 2023 snow water content averaged 24.20 inches for the eastern Box Elder/Cache County control sites. When this value was inserted into equation (4), the predicted target area snow water content was 36.27 inches. The measured average target area water content was 44.31 inches, which yields an observed/predicted ratio of 1.22 for the eastern Box Elder/Cache County portion of the target**.** The average increase for the 33 seeded seasons (excluding 2017 and 2023 as previously noted) is about 6%. The corresponding average estimated increase in snow water content (which could be attributed to seeding) is approximately 1.35 inches. Figure 5.7 provides a graphical plot of the ratios of observed to calculated snowpack for the eastern Box Elder/Cache County portion of the target. The snowpack normally begins accumulating in October. Consequently, snow water content measurements on April 1 include snow that fell during some non-seeded periods. This would typically result in a lower indicated percentage increase in April 1 snow water content when compared to December – March precipitation totals. Figure 5.8 is a scatterplot of the seeded and non-seeded seasons' data and corresponding linear regressions for each sample, and Figure 5.9 is a corresponding double mass plot as described previously (Section 4.3.1.4).

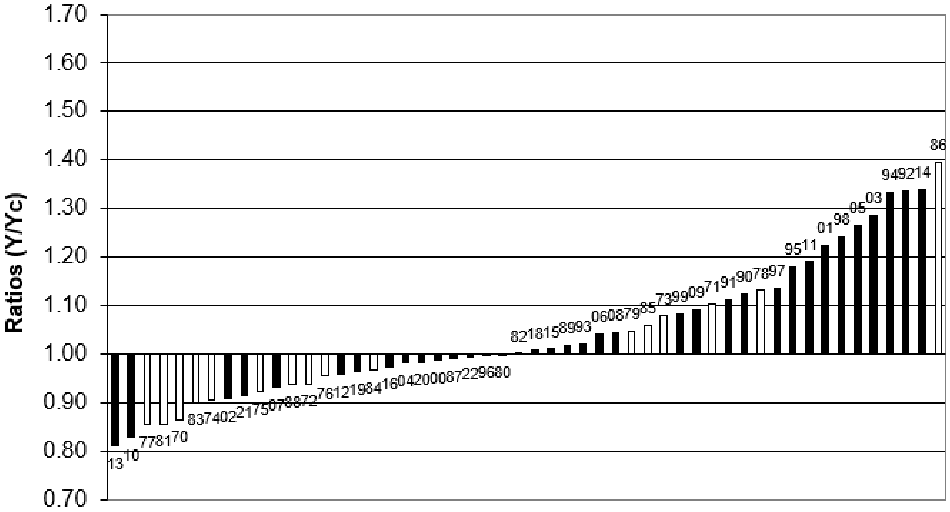


Figure 5.7 Observed/predicted ratios for 1970-2022 April 1st snow water content, using the linear regression technique, Eastern Box Elder/Cache Counties. White bars = historical (unseeded) seasons; black bars = seeded seasons

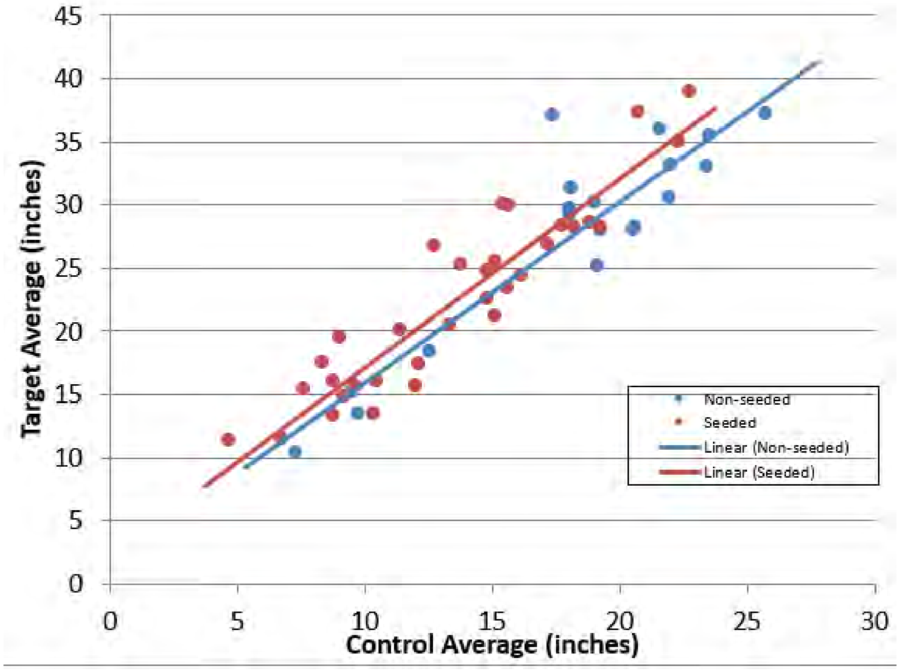


Figure 5.8 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for eastern Box Elder and Cache County snowpack linear regression.

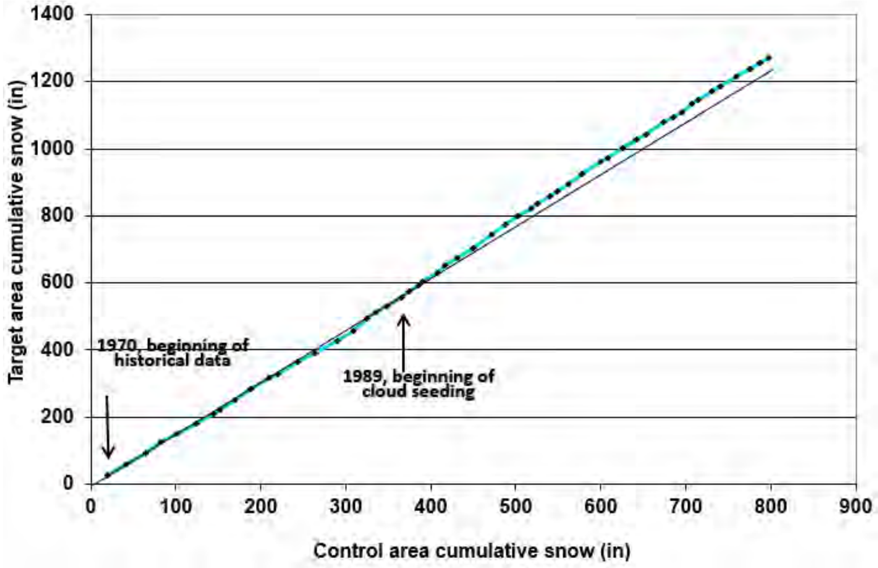


Figure 5.9 Double mass plot showing cumulative April 1 snow water content amounts for eastern Box Elder and Cache County target and control areas, water years 1970-2022.

In the northwestern Box Elder County portion of the target, the April 1, 2023 observed water content was 24.71 inches, with a predicted value of 25.09 inches. This yields an observed/predicted ratio of 0.98 for the northwestern Box Elder County portion of the target for this season. The average increase for the 29 previous seeded seasons is 13%, and the average estimated increase in snow water content is approximately 1.9 inches. Figure 5.10 is a bar chart showing the observed/predicted ratios for seeded and non-seeded seasons. Figure 5.11 is a corresponding scatterplot, and Figure 5.12 a double-mass plot as described previously.

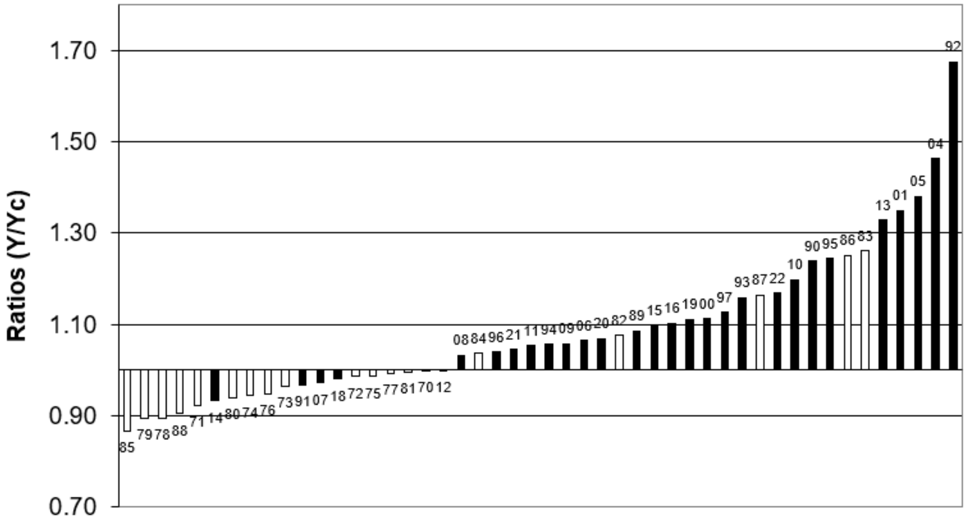


Figure 5.10 Observed/predicted ratios for 1970-2022 April 1st snow water content, using the linear regression technique, Northwest Box Elder County. White bars are historical (unseeded) seasons; black bars = seeded seasons; 1998, 1999, 2002, and 2003, are not shown because of no seeding in those years. 2017 was also excluded.

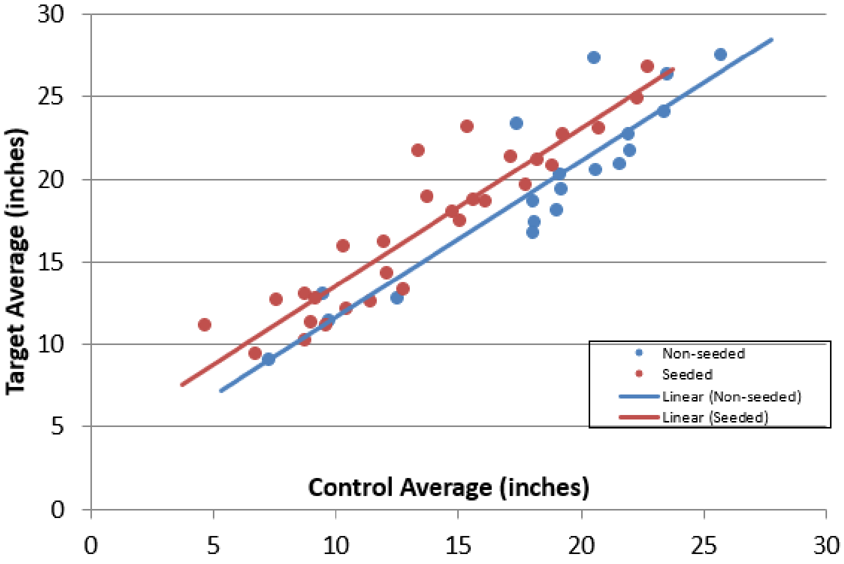


Figure 5.11 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for Northwest Box Elder County snowpack linear regression

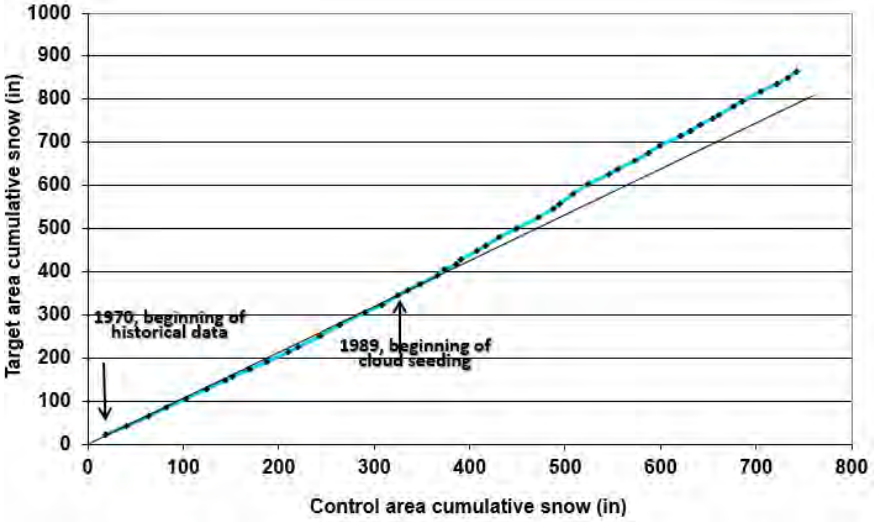


Figure 5.12 **Double mass plot showing cumulative April 1 snow water content amounts for Northwest Box Elder County target and control areas for water years 1970-2022 (plot excludes the water years 1998, 1999, 2002, and 2003, when no seeding was conducted, as well as water year 2017).**

5.3.2.5 Results of Multiple Linear Regression Snowpack Evaluation

The multiple regression evaluation resulted in ratios of 1.23 and 0.99 this season for the Eastern Box Elder/Cache County area and the Northwestern Box Elder County area, respectively. The long-term indications of these multiple regression for snowpack (through 2022) include a 13% increase, or about 2.5 inches of additional snow water content, based on the multiple linear regression for the Eastern Box Elder/Cache County area over 33 seasons of seeding. These results are higher than the linear regression equation's results for this data set, for largely unknown reasons. For northwestern Box Elder County, the long-term analysis shows a 9% increase (about 1.4 inches of additional snow water) based on the multiple linear equation for 29 seasons of seeding. These and other evaluation results are shown in detail in Appendix B.

5.4 Discussion of Evaluation Results

Results of the single-season target/control precipitation and snowpack evaluations presented in this section vary considerably from year to year. This inherent variability is due largely to differences in weather patterns from season to season. This is why individual year results, while potentially providing some insight, are not particularly accurate in reflecting the true magnitude of seeding effects and thus should be viewed with appropriate caution. **The strength in this type of evaluation lies in the long-term average of these results for many seeded seasons. These long-term averages show that winter season seeding programs such as this can increase seasonal precipitation on average in the range of about 5 to 15 percent over mountainous regions of the western U.S.**

This year's evaluation results for the eastern Box Elder and Cache County portion of the target area (December – March precipitation, and April 1 snowpack), and for Northwestern Box Elder County (April 1 snowpack) were quite extreme and anomalous, as is sometimes the case, but resulted in this year's data being excluded from all long-term calculations and graphs. Table 5-3 summarizes the cumulative results of the various target/control evaluations conducted for this program.

The long-term results for 33 seeded seasons in the Eastern Box Elder/Cache County portion of the target indicate 6-13% increases in April 1 snowpack (an average of 1.4-2.5 inches of additional water) and a 5-6% increase in December through March precipitation (a little under 1.0 inch of additional water). These cumulative results likely constitute reasonable estimates of the true seeding effects for this program, although the reasons for a difference in results between precipitation and snowpack is not really known. The natural seasonal variability which occurs in weather patterns and precipitation between target and control areas is expected to cause much more variation in the results of the single season mathematical target/control evaluation results, than for the actual effects of the seeding from one season to another which should be relatively consistent.

Table 5-3
Comparison of Results of Linear and Multiple Linear Analyses, for the Combination of all Seeded Seasons.

Area	Ratio Observed/Predicted		Excess Water (inches)	
	Linear	Multiple Linear	Linear	Multiple Linear
Cache/E. Box Elder Dec-Mar Precipitation (33 years)	1.05	1.06	+0.9	+1.0
Cache/E. Box Elder April 1 Snowpack (33 years)	1.06	1.13	+1.4	+2.5
NW Box Elder April 1 Snowpack (29 years)	1.13	1.09	+1.9	+1.4

Snowpack evaluations for the Northwestern Box Elder County portion of the target area this season produced long-term results indicating average increases for the 29 seeded seasons of +13% (linear) and +9% (multiple linear), which is equivalent to about 1.4 – 1.9 inches of additional snow water content. The evaluation results for Northwest Box Elder County are based on the two available target sites, George Creek and Vipont.

Appendix C contains the complete listing of historical and seeded season data and the regression equation information.

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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:

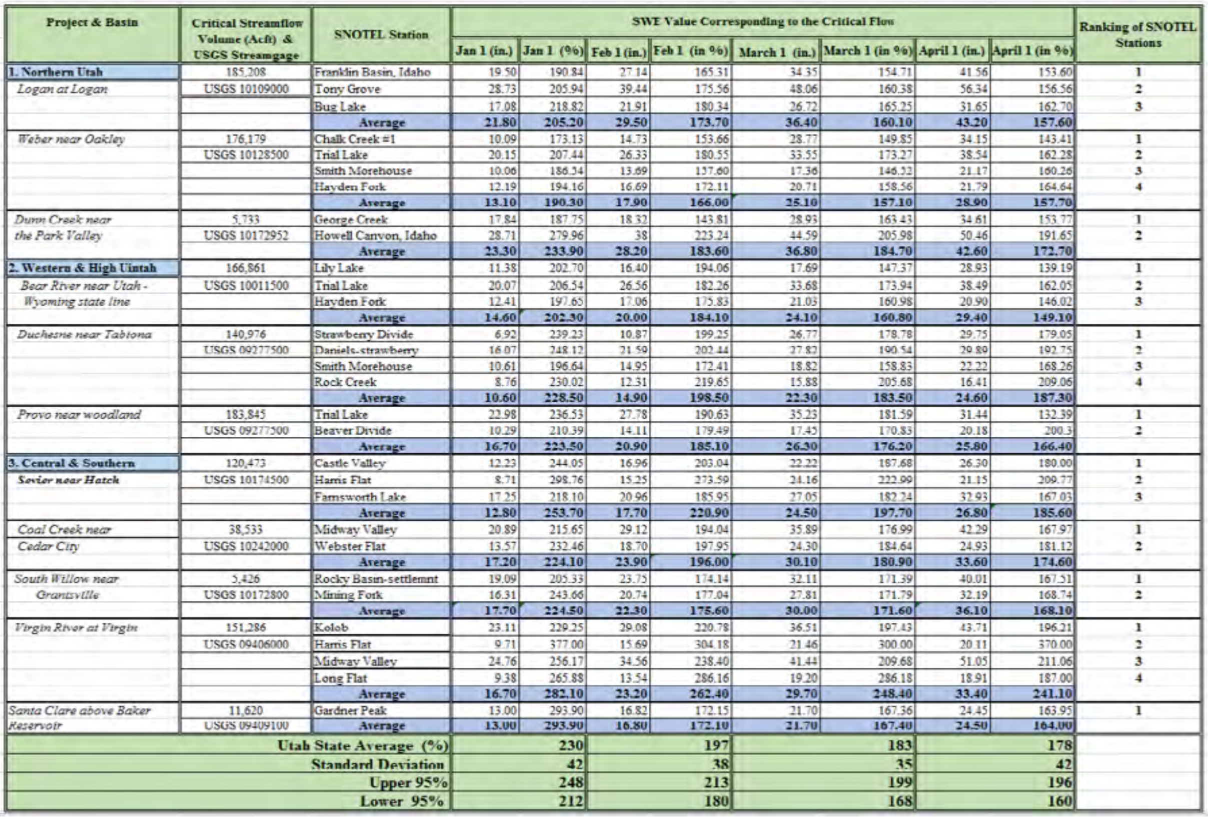
1. Excess snowpack accumulation

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	157.60	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	38,533	Midway Valley	20.89	215.65	29.12	194.04	35.89	176.99	42.29	167.97	1
Cedar City	USGS 10242000	Webster Flat	13.57	232.46	18.70	197.95	24.30	184.64	24.93	181.12	2
		Average	**17.20**	**224.10**	**23.90**	**196.00**	**30.10**	**180.90**	**33.60**	**174.60**	
South Willow near Grantsville	5,426	Rocky Basin-settlemnt	19.09	205.33	23.75	174.14	32.11	171.39	40.01	167.51	1
	USGS 10172800	Mining Fork	16.31	243.66	20.74	177.04	27.81	171.79	32.19	168.74	2
		Average	**17.70**	**224.50**	**22.30**	**175.60**	**30.00**	**171.60**	**36.10**	**168.10**	
Virgin River at Virgin	151,286	Kolob	23.11	229.25	29.08	220.78	36.51	197.43	43.71	196.21	1
	USGS 09406000	Harris Flat	9.71	377.00	15.69	304.18	21.46	300.00	20.11	370.00	2
		Midway Valley	24.76	256.17	34.56	238.40	41.44	209.68	51.05	211.06	3
		Long Flat	9.38	265.88	13.54	286.16	19.20	286.18	18.91	187.00	4
		Average	**16.70**	**282.10**	**23.20**	**262.40**	**29.70**	**248.40**	**33.40**	**241.10**	
Santa Clare above Baker Reservoir	11,620	Gardner Peak	13.00	293.90	16.82	172.15	21.70	167.36	24.45	163.95	1
	USGS 09409100	**Average**	**13.00**	**293.90**	**16.80**	**172.10**	**21.70**	**167.40**	**24.50**	**164.00**	
Utah State Average (%)			**230**		**197**		**183**		**178**		
Standard Deviation			**42**		**38**		**35**		**42**		
Upper 95%			**248**		**213**		**199**		**196**		
Lower 95%			**212**		**180**		**168**		**160**		

Snowpack-related suspension considerations will be assessed on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne River, Price-San Rafael, Dirty Devil, South Eastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. 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.

APPENDIX B: SEEDING OPERATIONS TABLE

Table B-1
Generator Hours – Northern Utah, 2022-2023, Storms 1-12

Storm	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Dates	**Dec 1-2**	**Dec 4-5**	**Dec 11-12**	**Dec 13**	**Dec 21**	**Dec 27-29**	**Jan 5-6**	**Jan 10-11**	**Jan 17**	**Jan 27-28**	**Feb 5-6**	**Feb 8**
SITE												
BE-1	8					11.25	18	15			14	
BE-2												
BE-3	9	5				11	21	3				
BE-4	9	5				11	21	3				
BE-5						11.25		15				
BE-6											4	
BE-7												
BE-8												
BE-9											6.5	
CV-1					4			15.75				2.25
CV-2	8				4			16		13.5		2.5
CV-3					10.5			18		10		3.5
CV-5	10				5.25	14		6				
CV-6	8.5				4			16				2.25
CV-7					4			15.25		17.5		2.25
CV-8				1.5	4.75	13.75	10.75	15.25				4.75
CV-9					4	5	11.5	16.25				
CV-10												
CV-11	8.5		5.5		6.25	14.5	5			10.75		
CV-12	8		12		11.5	3.25	20.25	16.5		18		
CV-13	8				10.75	12.75	20	13		18.75		
CV-14										4		

Storm	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Dates	**Dec 1-2**	**Dec 4-5**	**Dec 11-12**	**Dec 13**	**Dec 21**	**Dec 27-29**	**Jan 5-6**	**Jan 10-11**	**Jan 17**	**Jan 27-28**	**Feb 5-6**	**Feb 8**
CV-15	8	11.25	23.5			17	21	16.25		20.5		
CV-16					9.5		20	16.25				
CV-17	8		6.75	8	11.25	23.75	8.5	13.5	6.5	24		
CV-18					12	3.5	20	16.25	8	20		
CV-19		12	22.25		9	17.25	10	16.5		20.25		2.25
CV-20		12		7.25	10.5	3.5	19.5	14		3		
CV-21			21.5				15			6.5		
CV-22			13.75				5					
CV-23			20									
Richmond R												2.25
Huntsville R											3.5	
Storm	**93**	**45.25**	**125.25**	**16.75**	**121.25**	**172.75**	**246.5**	**276.75**	**14.5**	**186.75**	**24.5**	**17.5**

Table B-2
Generator Hours – Northern Utah, 2022-2023, Storms 13-21

Storm	13	14	15	16	17	18	19	20	21
Dates	**Feb 21-22**	**Feb 26-27**	**Mar 3**	**Mar 4-5**	**Mar 5-6**	**Mar 15**	**Mar 20-21**	**Mar 22-23**	**Mar 24**
SITE									
BE-1	6.5								
BE-2									
BE-3		10			4		7		
BE-4		10			4		7		
BE-5	6						4.5		
BE-6	5								
BE-7									
BE-8					4		5.5		
BE-9									
CV-1	5								6.5
CV-2	6.25								6.5
CV-3	5.75								
CV-5	18								
CV-6	5								
CV-7	18.25						16		3
CV-8	17	35					15.25		
CV-9		40	3.25			2.5	20		7
CV-10									
CV-11	5.75		3.5				8.75		11
CV-12	5.5		5		4	3	7		12
CV-13	4.5	37.25			5			20.5	11.25
CV-14	5.5	35			5		10.25	19.5	12

Storm	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Dates	**Feb 21-22**	**Feb 26-27**	**Mar 3**	**Mar 4-5**	**Mar 5-6**	**Mar 15**	**Mar 20-21**	**Mar 22-23**	**Mar 24**
CV-15	18.75	37.25		14	14		19	20.5	11.5
CV-16	17.5	10							11.5
CV-17	2.5	24.75							
CV-18	17.5	33					18		
CV-19							20		
CV-20	13.5	39.25		16			20	15.5	
CV-21		27.25						20.5	
CV-22					9			19	
CV-23				14.5	14				
Richmond R		23.25	2.75			3.75	8		
Huntsville R									
Storm	**183.75**	**338.75**	**11.75**	**44.5**	**49**	**5.5**	**178.25**	**115.5**	**92.25**

APPENDIX C: SEEDING EVALUATION TABLES

Eastern Box Elder and Cache County Dec-Mar Precipitation – Linear Regression

Regression (non-seeded) period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1970	17.93	17.85	23.05	0.77	-5.21
1971	19.45	20.37	24.99	0.82	-4.62
1972	18.88	19.50	24.26	0.80	-4.76
1973	14.28	20.90	18.43	1.13	2.47
1974	17.25	22.69	22.20	1.02	0.49
1975	17.05	23.46	21.94	1.07	1.52
1976	11.73	14.79	15.19	0.97	-0.40
1977	7.93	10.15	10.38	0.98	-0.23
1978	21.98	28.52	28.19	1.01	0.33
1979	18.55	22.85	23.85	0.96	-1.00
1980	21.45	29.57	27.52	1.07	2.05
1981	9.55	11.24	12.44	0.90	-1.19
1982	21.23	32.54	27.24	1.19	5.31
1983	16.45	20.51	21.18	0.97	-0.67
1984	20.43	25.44	26.22	0.97	-0.78
1985	9.63	14.91	12.53	1.19	2.38
1986	18.55	28.24	23.85	1.18	4.40
1987	8.73	11.64	11.39	1.02	0.25
1988	10.88	13.79	14.12	0.98	-0.33
Mean	15.89	20.47	20.47	1.00	0.00

Seeded period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1989	15.03	20.11	19.38	1.04	0.74
1990	9.85	12.21	12.82	0.95	-0.60
1991	10.00	14.71	13.01	1.13	1.71
1992	5.15	8.16	6.86	1.19	1.30
1993	17.13	23.44	22.04	1.06	1.40
1994	9.15	17.89	11.93	1.50	5.96
1995	12.45	23.00	16.11	1.43	6.89
1996	18.73	22.67	24.07	0.94	-1.40
1997	20.68	30.53	26.54	1.15	3.99

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1998	16.48	24.97	21.22	1.18	3.76
1999	14.28	19.20	18.43	1.04	0.77
2000	15.15	20.14	19.54	1.03	0.61
2001	9.23	13.87	12.03	1.15	1.85
2002	13.45	15.43	17.38	0.89	-1.95
2003	9.93	14.50	12.91	1.12	1.59
2004	14.58	17.40	18.81	0.93	-1.41
2005	11.60	22.06	15.04	1.47	7.02
2006	21.43	28.77	27.49	1.05	1.28
2007	12.23	12.91	15.83	0.82	-2.91
2008	16.93	23.81	21.79	1.09	2.03
2009	16.20	24.33	20.87	1.17	3.46
2010	12.13	14.00	15.70	0.89	-1.70
2011	17.43	28.46	22.42	1.27	6.04
2012	11.78	12.91	15.26	0.85	-2.34
2013	13.35	12.64	17.25	0.73	-4.61
2014	14.48	21.71	18.68	1.16	3.03
2015	11.08	11.53	14.37	0.80	-2.84
2016	17.80	20.93	22.90	0.91	-1.97
2017*	21.30	38.04	27.33	1.39	10.71
2018	11.63	14.47	15.07	0.96	-0.60
2019	15.38	22.57	19.82	1.14	2.75
2020	15.20	17.77	19.60	0.91	-1.83
2021	11.73	13.19	15.19	0.87	-2.01
2022	12.00	14.96	15.54	0.96	-0.59
2023*	16.50	33.53	21.25	1.58	12.28
Mean	13.74	18.64	17.75	**1.05**	**0.89**

* 2017 and 2023 not included in mean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.905497
R Square	0.819925
Adjusted R Square	0.809333
Standard Error	2.880614
Observations	19

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
	Coefficients	*Standard Error*	*t Stat*	*P-value*	
Intercept	0.330681	2.382764	0.13878	0.891255	
X Variable 1	1.267686	0.144088	8.798025	9.77E-08	

Eastern Box Elder and Cache County Dec-Mar Precipitation – Multiple Linear Regression

YEAR	Howell Canyon Tel	Bostetter R.S. Tel	Fawn Creek #2 Tel	Pole Creek Tel	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:								
1970	20.40	15.60	26.20	9.50	17.85	19.84	0.90	-1.99
1971	20.50	15.90	29.60	11.80	20.37	21.99	0.93	-1.62
1972	21.60	16.20	23.20	14.50	19.50	23.78	0.82	-4.28
1973	16.90	12.20	18.00	10.00	20.90	17.94	1.16	2.95
1974	18.20	13.60	20.70	16.50	22.69	23.61	0.96	-0.93
1975	14.90	11.20	29.00	13.10	23.46	20.75	1.13	2.71
1976	11.60	9.20	16.70	9.40	14.79	14.98	0.99	-0.19
1977	10.70	6.80	9.80	4.40	10.15	10.36	0.98	-0.21
1978	30.90	17.30	25.40	14.30	28.52	28.92	0.99	-0.41
1979	24.00	14.50	23.00	12.70	22.85	24.12	0.95	-1.27
1980	26.50	14.60	29.40	15.30	29.57	28.28	1.05	1.29
1981	10.70	11.00	11.10	5.40	11.24	10.37	1.08	0.88
1982	30.50	16.50	23.10	14.80	32.54	28.96	1.12	3.59
1983	26.10	11.00	18.80	9.90	20.51	23.43	0.88	-2.92
1984	24.20	16.60	26.00	14.90	25.44	25.81	0.99	-0.37
1985	11.70	9.20	11.30	6.30	14.91	12.03	1.24	2.89
1986	27.40	15.20	19.90	11.70	28.24	24.75	1.14	3.50
1987	11.30	6.60	10.20	6.80	11.64	12.60	0.92	-0.96
1988	17.40	8.20	10.10	7.80	13.79	16.44	0.84	-2.66
Mean	19.76	12.71	20.08	11.01	20.47	20.47	1.00	0.00

Seeded period:

YEAR	Howell Canyon Tel	Bostetter R.S. Tel	Fawn Creek #2 Tel	Pole Creek Tel	YOBS	YCALC	RATIO	EXCESS

1989	19.10	10.80	20.60	9.60	20.11	19.52	1.03	0.60
1990	11.10	8.20	13.00	7.10	12.21	12.72	0.96	-0.51
1991	11.90	8.00	13.80	6.30	14.71	12.71	1.16	2.00
1992	6.90	3.80	5.80	4.10	8.16	8.14	1.00	0.02
1993	24.20	15.10	18.90	10.30	23.44	21.78	1.08	1.66
1994	12.60	7.50	11.10	5.40	17.89	12.20	1.47	5.69
1995	16.30	11.00	14.80	7.70	23.00	15.73	1.46	7.27
1996	27.30	16.40	19.30	11.90	22.67	24.51	0.93	-1.83
1997	32.20	18.40	21.40	10.70	30.53	26.20	1.17	4.33
1998	28.00	13.30	16.70	7.90	24.97	22.23	1.12	2.74
1999	21.30	13.30	15.30	7.20	19.20	17.74	1.08	1.46
2000	22.30	13.10	17.60	7.60	20.14	18.94	1.06	1.20

YEAR	Howell Canyon Tel	Bostetter R.S. Tel	Fawn Creek #2 Tel	Pole Creek Tel	YOBS	YCALC	RATIO	EXCESS
2001	11.20	8.20	11.90	5.60	13.87	11.51	1.21	2.36
2002	18.80	13.10	14.20	7.70	15.43	16.61	0.93	-1.18
2003	12.90	8.60	12.50	5.70	14.50	12.53	1.16	1.97
2004	19.40	13.60	17.30	8.00	17.40	17.46	1.00	-0.06
2005	14.90	11.70	12.10	7.70	22.06	14.45	1.53	7.61
2006	32.20	19.80	22.40	11.30	28.77	26.47	1.09	2.30
2007	18.20	9.90	13.40	7.40	12.91	16.64	0.78	-3.73
2008	28.00	14.80	15.80	9.10	23.81	22.70	1.05	1.12
2009	24.00	14.10	17.10	9.60	24.33	21.13	1.15	3.20
2010	17.80	10.70	12.90	7.10	14.00	15.95	0.88	-1.95
2011	24.40	15.50	18.90	10.90	28.46	22.26	1.28	6.20
2012	19.40	14.10	6.80	6.80	12.91	15.12	0.85	-2.21
2013	18.70	13.00	14.20	7.50	12.64	16.43	0.77	-3.78
2014	22.40	14.20	14.20	7.10	21.71	17.95	1.21	3.76
2015	16.60	10.80	11.20	5.70	11.53	13.98	0.82	-2.45
2016	26.80	16.90	16.60	10.90	20.93	23.02	0.91	-2.09
2017*	31.80	19.70	21.40	12.30	38.04	26.90	1.41	11.14
2018	16.30	10.60	11.90	7.70	14.47	15.45	0.94	-0.98
2019	20.30	15.20	15.00	11.00	22.57	19.59	1.15	2.98
2020	20.00	15.90	14.70	10.20	17.77	18.63	0.95	-0.86
2021	15.50	11.70	11.70	8.00	13.19	14.96	0.88	-1.78
2022	18.40	12.30	9.20	8.10	14.96	16.23	0.92	-1.27
2023*	25.10	15.60	14.20	11.10	33.53	22.19	1.51	11.34
Mean	19.68	12.53	14.61	8.15	18.64	17.62	**1.06**	**1.02**

* 2017 and 2023 not included in mean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.93659
R Square	0.87719
Standard Error	2.62139
Observations	19

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	1.24114	2.3293	0.5328	0.602
X Variable 1	0.56527	0.15918	3.5512	0.003
X Variable 2	-0.21731	0.39505	0.5501	0.590
X Variable 3	0.12575	0.17583	0.7151	0.486
X Variable 4	0.75375	0.32639	2.3093	0.036

Eastern Box Elder and Cache County April 1 Snow – Linear Regression

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:					
1970	19.14	25.11	28.96	0.87	-3.84
1971	21.62	35.99	32.52	1.11	3.47
1972	23.42	33.01	35.10	0.94	-2.09
1973	18.06	29.64	27.41	1.08	2.24
1974	20.64	28.23	31.11	0.91	-2.88
1975	21.96	30.53	33.01	0.92	-2.48
1976	19.26	27.90	29.13	0.96	-1.23
1977	7.30	10.34	11.95	0.87	-1.61
1978	18.12	31.21	27.49	1.14	3.72
1979	19.02	30.21	28.78	1.05	1.43
1980	22.04	33.14	33.12	1.00	0.02
1981	9.76	13.37	15.48	0.86	-2.11
1982	23.54	35.40	35.28	1.00	0.12
1983	20.58	27.99	31.02	0.90	-3.04
1984	25.74	37.19	38.44	0.97	-1.25
1985	18.08	29.16	27.43	1.06	1.72
1986	17.38	37.01	26.43	1.40	10.59
1987	9.52	15.13	15.14	1.00	-0.01
1988	12.54	18.37	19.48	0.94	-1.11
Mean	18.30	27.84	27.75	1.00	0.09

YEAR XOBS YOBS YCALC RATIO EXCESS

Seeded period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1989	18.24	28.23	27.66	1.02	0.56
1990	8.80	16.01	14.11	1.14	1.91
1991	11.42	20.01	17.87	1.12	2.15
1992	4.72	11.26	8.24	1.37	3.01
1993	17.18	26.79	26.14	1.02	0.64
1994	9.02	19.41	14.42	1.35	4.99
1995	13.76	25.17	21.23	1.19	3.94
1996	18.84	28.56	28.53	1.00	0.03
1997	22.74	38.84	34.13	1.14	4.72
1998	15.68	29.94	23.99	1.25	5.96
1999	14.82	24.76	22.75	1.09	2.01
2000	14.80	22.53	22.72	0.99	-0.19
2001	7.62	15.39	12.41	1.24	2.98
2002	15.16	21.20	23.24	0.91	-2.04
2003	8.36	17.51	13.47	1.30	4.04
2004	13.38	20.41	20.68	0.99	-0.27
2005	15.42	30.01	23.61	1.27	6.40
2006	22.32	34.96	33.52	1.04	1.43
2007	8.80	13.29	14.11	0.94	-0.82
2008	17.76	28.29	26.97	1.05	1.31
2009	15.10	25.41	23.15	1.10	2.26
2010	12.00	15.60	18.70	0.83	-3.10
2011	20.76	37.31	31.28	1.19	6.03
2012	10.50	15.97	16.55	0.97	-0.58
2013	10.36	13.37	16.35	0.82	-2.97
2014	12.78	26.70	19.82	1.35	6.88
2015	6.78	11.49	11.37	1.01	0.12
2016	15.62	23.39	24.01	0.97	-0.62
2017*	18.96	33.59	28.78	1.17	4.80
2018	9.64	15.57	15.46	1.01	0.12
2019	19.30	28.19	29.27	0.96	-1.08
2020	16.14	24.34	24.75	0.98	-0.41
2021	12.12	17.40	19.00	0.92	-1.60
2022	9.20	14.74	14.83	0.99	-0.08
2023*	24.20	44.31	36.27	1.22	8.04
Mean	13.61	22.49	21.13	**1.06**	**1.35**

* 2017 and 2023 not included in mean values

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.911075

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
R Square	0.830058				
Adjusted R Square	0.820062				
Standard Error	3.395702				
Observations	19				

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	957.452	957.452	83.03436	5.94E-08
Residual	17	196.0235	11.53079		
Total	18	1153.475			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.465645	2.997273	0.488993	0.631096	-4.85806	7.789347
X Variable 1	1.436298	0.157622	9.112319	5.94E-08	1.103745	1.768851

Eastern Box Elder and Cache County April 1 Snow – Multiple Linear Regression

YEAR	Magic Mtn Pil	Badger Gulch Sc	Big Bend Pil	Sedgewick Pk Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:									
1970	23.30	15.30	10.80	28.10	18.20	25.11	28.04	0.90	-2.93
1971	24.80	14.10	12.70	35.20	21.30	35.99	33.48	1.07	2.51
1972	33.40	20.40	10.90	34.40	18.00	33.01	34.33	0.96	-1.31
1973	21.60	14.40	8.90	25.60	19.80	29.64	28.37	1.04	1.27
1974	25.20	20.00	11.90	28.10	18.00	28.23	29.22	0.97	-0.99
1975	24.40	18.70	15.70	29.80	21.20	30.53	30.15	1.01	0.38
1976	22.00	15.50	12.70	30.20	15.90	27.90	26.45	1.05	1.45
1977	8.40	6.00	3.10	11.30	7.70	10.34	9.02	1.15	1.32
1978	19.20	12.40	9.20	24.90	24.90	31.21	30.91	1.01	0.31
1979	19.60	14.60	10.10	27.50	23.30	30.21	31.64	0.96	-1.42
1980	21.50	15.70	13.70	31.30	28.00	33.14	36.27	0.91	-3.13
1981	12.00	7.20	2.00	13.50	14.10	13.37	16.79	0.80	-3.41
1982	28.10	18.20	13.70	31.60	26.10	35.40	36.30	0.98	-0.90
1983	24.60	14.60	15.70	23.70	24.30	27.99	27.22	1.03	0.77
1984	32.00	19.50	18.00	29.80	29.40	37.19	36.14	1.03	1.04
1985	20.80	14.70	9.10	25.50	20.30	29.16	28.67	1.02	0.49
1986	19.10	16.10	4.40	24.30	23.00	37.01	33.16	1.12	3.86
1987	10.60	8.80	2.30	14.10	11.80	15.13	15.71	0.96	-0.58
1988	16.10	9.00	6.80	16.40	14.40	18.37	17.08	1.08	1.29
Mean	21.41	14.48	10.09	25.54	19.98	27.84	27.84	1.00	0.00

YEAR	Magic Mtn Pil	Badger Gulch Sc	Big Bend Pil	Sedgewick Pk Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
Seeded period:									
YEAR	Magic Mtn Pil	Badger Gulch Sc	Big Bend Pil	Sedgewick Pk Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
1989	23.60	16.20	10.50	23.10	17.80	28.23	25.15	1.12	3.08
1990	10.20	7.70	0.00	13.30	12.80	16.01	16.84	0.95	-0.82
1991	14.70	7.50	2.40	16.60	15.90	20.01	20.20	0.99	-0.18
1992	3.60	3.00	0.00	10.10	6.90	11.26	7.92	1.42	3.34
1993	18.10	14.60	8.40	23.50	21.30	26.79	28.42	0.94	-1.63
1994	11.60	8.40	0.40	14.60	10.10	19.41	15.63	1.24	3.79
1995	15.70	10.40	3.90	21.90	16.90	25.17	24.65	1.02	0.52
1996	21.20	14.70	10.20	25.70	22.40	28.56	29.87	0.96	-1.32
1997	26.90	18.60	8.40	32.50	27.30	38.84	40.87	0.95	-2.03
1998	18.20	11.50	7.20	22.90	18.60	29.94	25.35	1.18	4.59
1999	20.00	13.80	8.00	20.80	11.50	24.76	18.95	1.31	5.81
2000	18.50	11.90	8.80	17.60	17.20	22.53	20.22	1.11	2.31
2001	11.40	6.10	2.00	10.10	8.50	15.39	9.74	1.58	5.64
2002	20.90	15.80	10.40	15.80	12.90	21.20	16.45	1.29	4.75
2003	10.60	4.20	2.00	14.70	10.30	17.51	13.24	1.32	4.27
2004	20.20	13.00	3.60	19.60	10.50	20.41	19.57	1.04	0.85
2005	16.70	9.80	7.70	20.70	22.20	30.01	25.82	1.16	4.20
2006	28.20	18.20	14.50	27.00	23.70	34.96	31.09	1.12	3.87
2007	14.00	5.20	1.80	14.40	8.60	13.29	12.40	1.07	0.88
2008	20.00	16.80	11.60	21.40	19.00	28.29	24.46	1.16	3.82
2009	20.40	10.20	10.10	20.70	14.10	25.41	18.39	1.38	7.02
2010	15.70	11.20	8.40	14.70	10.00	15.60	12.47	1.25	3.13
2011	21.80	15.40	13.80	28.10	24.70	37.31	31.49	1.18	5.82
2012	17.20	10.90	2.80	15.70	5.90	15.97	12.93	1.24	3.05
2013	15.20	9.60	2.00	15.50	9.50	13.37	15.49	0.86	-2.12
2014	17.70	11.40	2.20	18.30	14.30	26.70	21.80	1.22	4.90
2015	13.00	5.40	0.00	10.60	4.90	11.49	8.12	1.41	3.37
2016	22.40	14.70	9.50	19.20	12.30	23.39	18.24	1.28	5.14
2017*	19.80	15.10	10.10	26.60	23.20	33.59	31.20	1.08	2.38
2018	12.70	6.90	2.70	18.30	7.60	15.57	14.12	1.10	1.45
2019	21.20	17.70	10.40	23.30	23.90	28.19	30.65	0.92	-2.46
2020	21.40	15.60	8.40	19.80	15.50	24.34	22.08	1.10	2.26
2021	16.60	12.40	6.70	14.90	10.00	17.40	14.07	1.24	3.33
2022	14.90	7.00	2.00	11.20	10.90	14.74	12.89	1.14	1.85
2023*	28.40	20.60	14.70	33.70	23.60	44.31	36.02	1.23	8.29
Mean	17.41	11.39	6.08	18.68	14.48	22.49	19.99	**1.13**	**2.50**

* 2017 and 2023 not included in mean values

YEAR	Magic Mtn Pil	Badger Gulch Sc	Big Bend Pil	Sedgewick Pk Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9708
R Square	0.9425

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*	*Upper 95.0%*
Intercept	-5.2440	2.43758	-2.1513	0.0508	-10.51	0.022	-10.51	0.02203	8.29924
X Var 1	0.0570	0.2439	0.2337	0.8188	-0.47	0.5841	-0.47	58409	0.63945
X Var 2	0.3935	0.3366	1.1691	0.2633	-0.3337	1.1208	0.3337	1.1208	1.91336
X Var 3	0.5596	0.2273	-2.4613	0.0286	-1.0509	-0.0684	1.0509	-0.0684	0.403
X Var 4	0.6219	0.1739	3.5747	0.0034	0.2461	0.9978	0.2461	0.9977	1.65304
X Var 5	0.7967	0.1405	5.6698	8E-05	0.4932	1.1004	0.4932	1.1003	

Northwest Box Elder County – April 1 Snow Water Content Linear Regression

Regression (non-seeded) period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1970	19.14	20.25	20.29	1.00	-0.04
1971	21.62	20.90	22.65	0.92	-1.75
1972	23.42	24.00	24.35	0.99	-0.35
1973	18.06	18.60	19.27	0.97	-0.67
1974	20.64	20.50	21.72	0.94	-1.22
1975	21.96	22.65	22.97	0.99	-0.32
1976	19.26	19.35	20.41	0.95	-1.06
1977	7.30	9.00	9.07	0.99	-0.07
1978	18.12	17.30	19.33	0.90	-2.03
1979	19.02	18.05	20.18	0.89	-2.13
1980	22.04	21.65	23.04	0.94	-1.39
1981	9.76	11.35	11.40	1.00	-0.05
1982	23.54	26.30	24.47	1.07	1.83
1983	20.58	27.30	21.66	1.26	5.64
1984	25.74	27.50	26.55	1.04	0.95
1985	18.08	16.70	19.29	0.87	-2.59
1986	17.38	23.30	18.63	1.25	4.67
1987	9.52	13.00	11.17	1.16	1.83
1988	12.54	12.70	14.04	0.90	-1.34
Mean	18.30	19.49	19.50	1.00	0.00

Seeded Period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1989	18.24	21.10	19.44	1.09	1.66
1990	8.80	13.00	10.49	1.24	2.51
1991	11.42	12.55	12.98	0.97	-0.43
1992	4.72	11.10	6.62	1.68	4.48
1993	17.18	21.35	18.44	1.16	2.91
1994	9.02	11.30	10.70	1.06	0.60
1995	13.76	18.90	15.19	1.24	3.71
1996	18.84	20.80	20.01	1.04	0.79
1997	22.74	26.70	23.71	1.13	2.99
1998*	15.68	19.40	17.01	1.14	2.39
1999*	14.82	16.10	16.20	0.99	-0.10
2000	14.80	18.00	16.18	1.11	1.82
2001	7.62	12.65	9.37	1.35	3.28
YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
2002*	15.16	18.90	16.52	1.14	2.38
2003*	8.36	9.80	10.08	0.97	-0.28
2004	13.38	21.70	14.83	1.46	6.87
2005	15.42	23.15	16.77	1.38	6.38
2006	22.32	24.80	23.31	1.06	1.49
2007	8.80	10.20	10.49	0.97	-0.29
2008	17.76	19.60	18.99	1.03	0.61
2009	15.10	17.40	16.46	1.06	0.94
2010	12.00	16.20	13.53	1.20	2.67
2011	20.76	23.00	21.83	1.05	1.17
2012	10.50	12.10	12.10	1.00	0.00
2013	10.36	15.90	11.97	1.33	3.93
2014	12.78	13.30	14.27	0.93	-0.97
2015	6.78	9.40	8.58	1.10	0.82
2016	15.62	18.70	16.96	1.10	1.74
2017**	18.96	20.30	20.12	1.01	0.18
2018	9.64	11.10	11.29	0.98	-0.19
2019	19.30	22.70	20.45	1.11	2.25
2020	16.14	18.64	17.45	1.07	1.18
2021	12.12	14.25	13.64	1.04	0.61
2022	9.20	12.71	10.87	1.17	1.84
2023*	24.20	24.71	25.09	0.98	-0.39
Mean	13.62	16.98	15.07	**1.13**	**1.91**

* No seeding in these seasons, excluded from mean

** 2017 and 2023 not included in mean values

Regression Statistics	
Multiple R	0.910073

R Square	0.828234
Adjusted R Square	0.81813
Standard Error	2.258002
Observations	19

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.152556	1.984266	1.084812	0.29315	-2.03388	6.338997
X Variable 1	0.947606	0.104664	9.053822	6.51E-08	0.726784	1.168427

Northwest Box Elder County – April 1 Snow Water Content Multiple Regression

YEAR	Magic Mtn Pil	Badger Gulch SC	Sedgewick Pk Pil	Big Bend Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:									
1970	23.3	15.3	28.1	10.8	18.2	20.3	19.57	1.03	0.68
1971	24.8	14.1	35.2	12.7	21.3	20.9	19.64	1.06	1.26
1972	33.4	20.4	34.4	10.9	18.0	24.0	24.21	0.99	-0.21
1973	21.6	14.4	25.6	8.9	19.8	18.6	19.30	0.96	-0.70
1974	25.2	20	28.1	11.9	18.0	20.5	22.35	0.92	-1.85
1975	24.4	18.7	29.8	15.7	21.2	22.7	22.78	0.99	-0.13
1976	22	15.5	30.2	12.7	15.9	19.4	18.31	1.06	1.04
1977	8.4	6	11.3	3.1	7.7	9.0	8.67	1.04	0.33
1978	19.2	12.4	24.9	9.2	24.9	17.3	19.45	0.89	-2.15
1979	19.6	14.6	27.5	10.1	23.3	18.1	19.66	0.92	-1.61
1980	21.5	15.7	31.3	13.7	28.0	21.7	22.20	0.98	-0.55
1981	12	7.2	13.5	2.0	14.1	11.4	12.07	0.94	-0.72
1982	28.1	18.2	31.6	13.7	26.1	26.3	24.94	1.05	1.36
1983	24.6	14.6	23.7	15.7	24.3	27.3	23.21	1.18	4.09
1984	32	19.5	29.8	18.0	29.4	27.5	28.89	0.95	-1.39
1985	20.8	14.7	25.5	9.1	20.3	16.7	19.35	0.86	-2.65
1986	19.1	16.1	24.3	4.4	23.0	23.3	19.83	1.18	3.47
1987	10.6	8.8	14.1	2.3	11.8	13.0	11.43	1.14	1.57
1988	16.1	9	16.4	6.8	14.4	12.7	14.55	0.87	-1.85

YEAR	Magic Mtn Pil	Badger Gulch SC	Sedgewick Pk Pil	Big Bend Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
Mean	21.41	14.48	25.54	10.1	19.98	19.49	19.49	1.00	0.00

YEAR	Magic Mtn Pil	Badger Gulch SC	Sedgewick Pk Pil	Big Bend	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
Seeded Period:									
1989	23.6	16.2	23.1	10.5	17.8	21.1	20.77	1.02	0.33
1990	10.2	7.7	13.3	0.0	12.8	13.0	10.98	1.18	2.02
1991	14.7	7.5	16.6	2.4	15.9	12.6	13.28	0.95	-0.73
1992	3.6	3	10.1	0.0	6.9	11.1	5.19	2.14	5.91
1993	18.1	14.6	23.5	8.4	21.3	21.4	18.93	1.13	2.42
1994	11.6	8.4	14.6	0.4	10.1	11.3	10.70	1.06	0.60
1995	15.7	10.4	21.9	3.9	16.9	18.9	14.48	1.31	4.42
1996	21.2	14.7	25.7	10.2	22.4	20.8	20.31	1.02	0.49
1997	26.9	18.6	32.5	8.4	27.3	26.7	24.22	1.10	2.48
1998*	18.2	11.5	22.9	7.2	18.6	19.4	16.68	1.16	2.72
1999*	20.0	13.8	20.8	8.0	11.5	16.1	16.42	0.98	-0.32
2000	18.5	11.9	17.6	8.8	17.2	18.0	17.64	1.02	0.36
2001	11.4	6.1	10.1	2.0	8.5	12.7	10.11	1.25	2.54
2002*	20.9	15.8	15.8	10.4	12.9	18.9	19.26	0.98	-0.36
2003*	10.6	4.2	14.7	2.0	10.3	9.8	8.81	1.11	0.99
2004	20.2	13.0	19.6	3.6	10.5	21.7	15.43	1.41	6.27
2005	16.7	9.8	20.7	7.7	22.2	23.2	17.07	1.36	6.08
2006	28.2	18.2	27.0	14.5	23.7	24.8	25.09	0.99	-0.29
2007	14.0	5.2	14.4	1.8	8.6	10.2	9.91	1.03	0.29
2008	20.0	16.8	21.4	11.6	19.0	19.6	20.59	0.95	-0.99
2009	20.4	10.2	20.7	10.1	14.1	17.4	16.18	1.08	1.22
2010	15.7	11.2	14.7	8.4	10.0	16.2	14.39	1.13	1.81
2011	21.8	15.4	28.1	13.8	24.7	23.0	21.65	1.06	1.35
2012	17.2	10.9	15.7	2.8	5.9	12.1	12.50	0.97	-0.40
2013	15.2	9.6	15.5	2.0	9.5	15.9	12.36	1.29	3.54
2014	17.7	11.4	18.3	2.2	14.3	13.3	15.16	0.88	-1.86
2015	13.0	5.4	10.6	0.0	4.9	9.4	8.83	1.07	0.57
2016	22.4	14.7	19.2	9.5	12.3	18.7	18.41	1.02	0.29
2017**	19.8	15.1	26.6	10.1	23.2	20.3	20.08	1.01	0.22
2018	12.7	6.9	18.3	2.7	7.6	11.1	9.27	1.20	1.83
2019	21.2	17.7	23.3	10.4	23.9	22.7	22.54	1.01	0.16
2020	21.4	15.6	19.8	8.4	15.5	18.6	19.26	0.97	-0.62
2021	16.6	12.4	14.9	6.7	10.0	14.3	14.96	0.95	-0.71
2022	14.9	7.0	11.2	2.0	10.9	12.7	12.36	1.03	0.35
2023	28.4	20.6	33.7	14.7	23.6	24.7	25.01	0.99	-0.31
Mean	17.4	11.4	18.7	6.0	14.6	17.0	15.6	**1.09**	**1.37**

YEAR	Magic Mtn Pil	Badger Gulch SC	Sedgewick Pk Pil	Big Bend Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS

* No seeding in these seasons, not included in mean

** 2017 and 2023 not included in mean values

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.93784
R Square	0.879544
Standard Error	2.162331
Observations	19

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.088813	2.333923	0.8949796	0.387069	-2.9533192	7.130946
X Variable 1	0.357386	0.233593	1.5299493	0.149993	-0.1472617	0.862034
X Variable 2	0.428867	0.322314	1.3305894	0.206193	-0.2674492	1.125184
X Variable 3	-0.17568	0.166582	1.0546019	0.310814	-0.535557	0.184201
X Variable 4	0.134263	0.217714	0.6166958	0.548084	-0.3360791	0.604606
X Variable 5	0.3341	0.134553	2.4830346	0.027453	0.0434157	0.624784

APPENDIX D: GLOSSARY OF RELEVANT METEOROLOGICAL TERMS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Pressure Heights:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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