Cloud Seeding Annual Report

Northern Utah Program
2019-2020 Winter Season

Prepared For:

Bear River Water Conservancy District

Box Elder County

Cache County

State of Utah, Division of Water Resources

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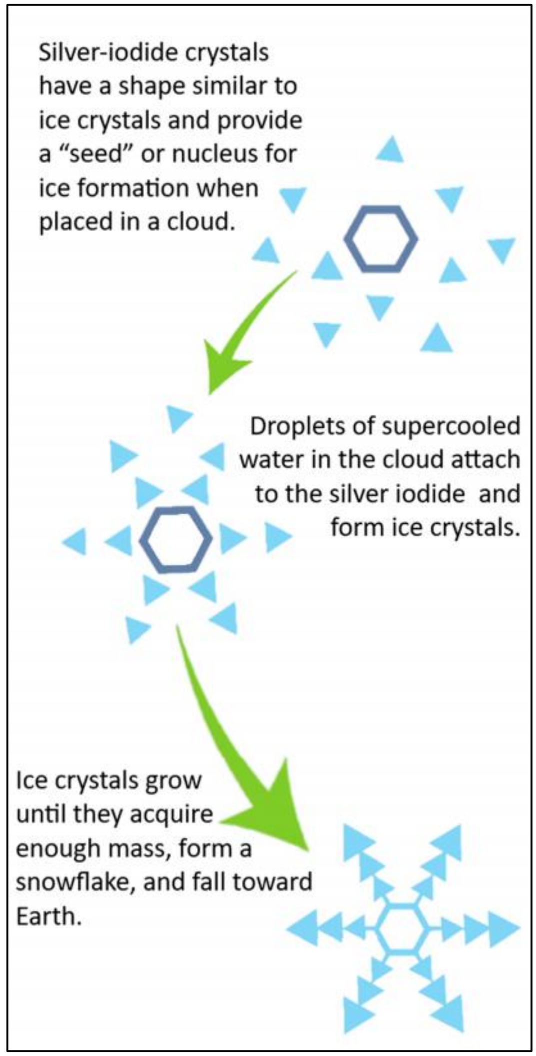
WEATHER MODIFICATION

The Science Behind Cloud Seeding

The Science

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

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

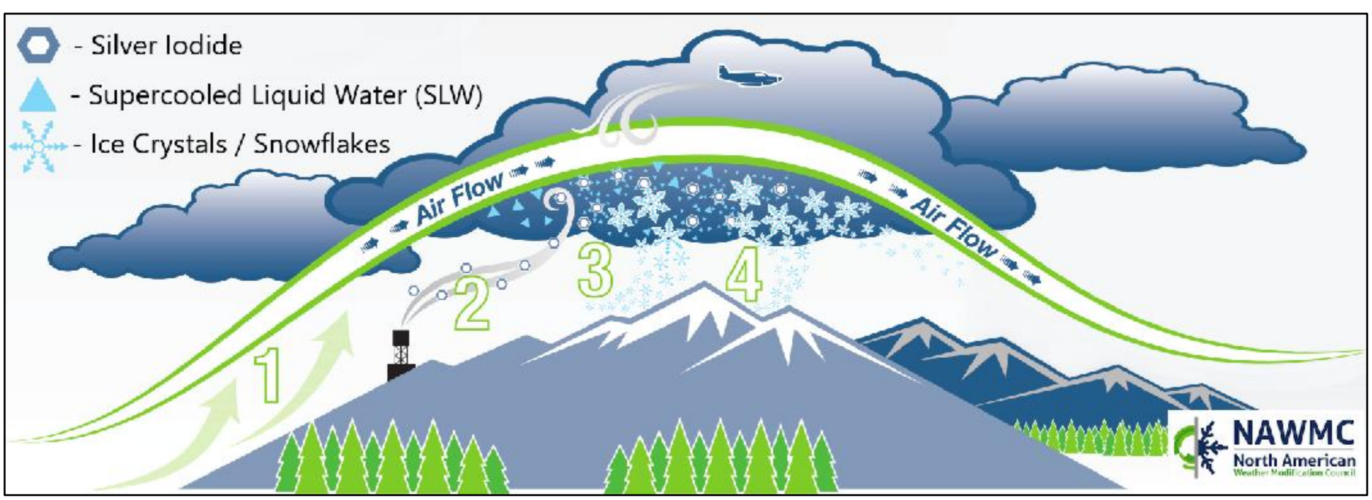


Safety

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

Effectiveness

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



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EXECUTIVE SUMMARY

In 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, or CNG) sites, containing a 2% silver iodide solution. The goal of the seeding program is to augment wintertime snowpack/precipitation over the seeded watersheds. Cost sharing for the seeding program is provided by the Utah Division of Water Resources.

Precipitation and snowfall were generally near normal during the 2019-2020 winter season. A total of 1,797.5 CNG hours were conducted during 18 storm periods for the core program this season. There were no seeding suspensions during the 2019-2020 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 6-7% 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 1.0 – 1.2” of precipitation seasonally. Similar regressions with April 1 snow water content data have suggested increases anywhere from 7-13%, implying increases between about 1.5 – 2.5” 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.

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 last 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 2019-2020 winter season. NAWC has been active in cloud seeding since 1950, 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 to conduct a cloud seeding project be published in local area newspapers at least three weeks before the start of a 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 2019-2020 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 during 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.

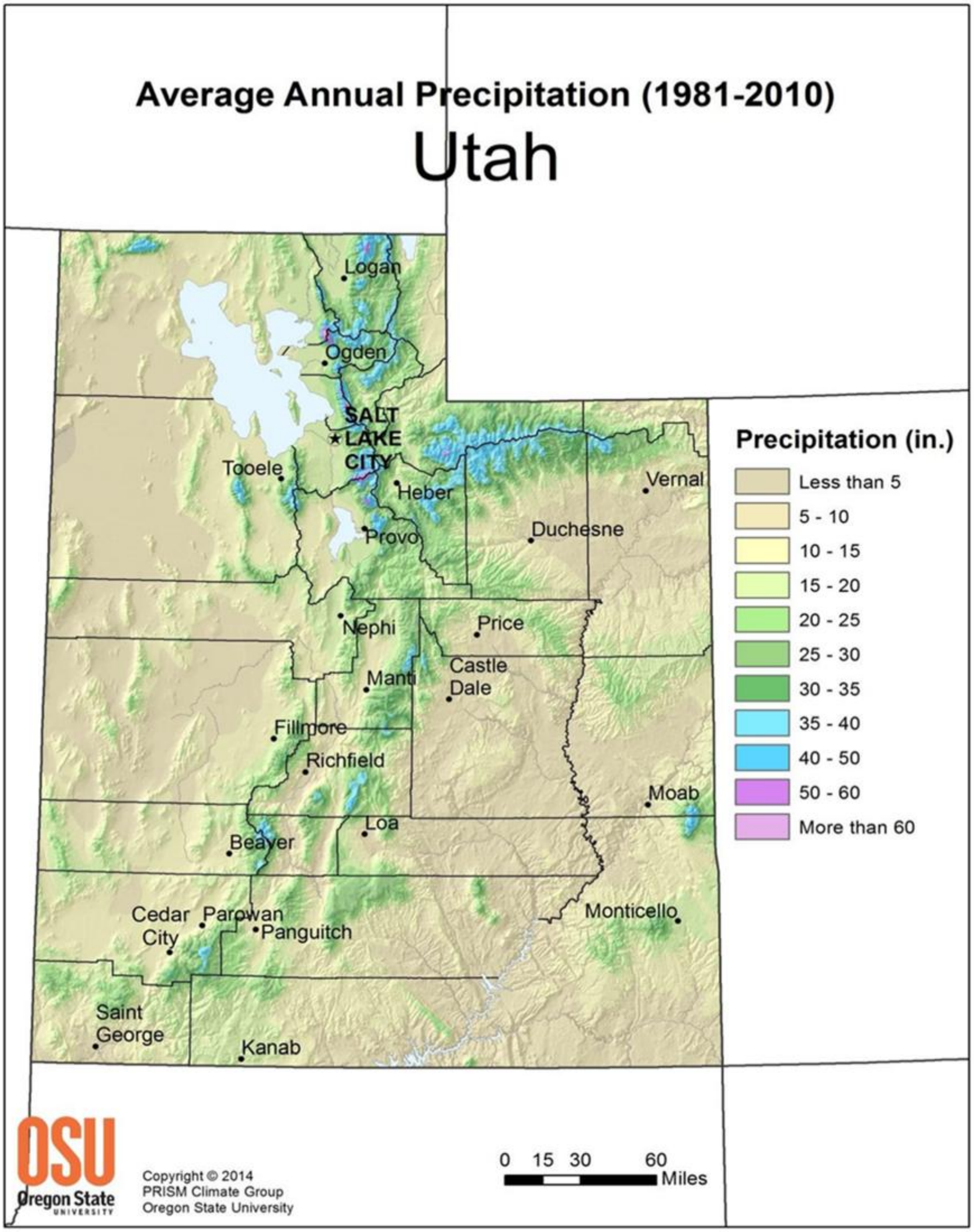


Figure 1.1 Average annual precipitation in Utah

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 Seedability 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 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 2019, 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 in the Bear River Range. 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 seeding generators are also shown in Figure 2.1.

The cloud seeding equipment consists of ground-based cloud nuclei generator (CNG) 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 and also provides 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.

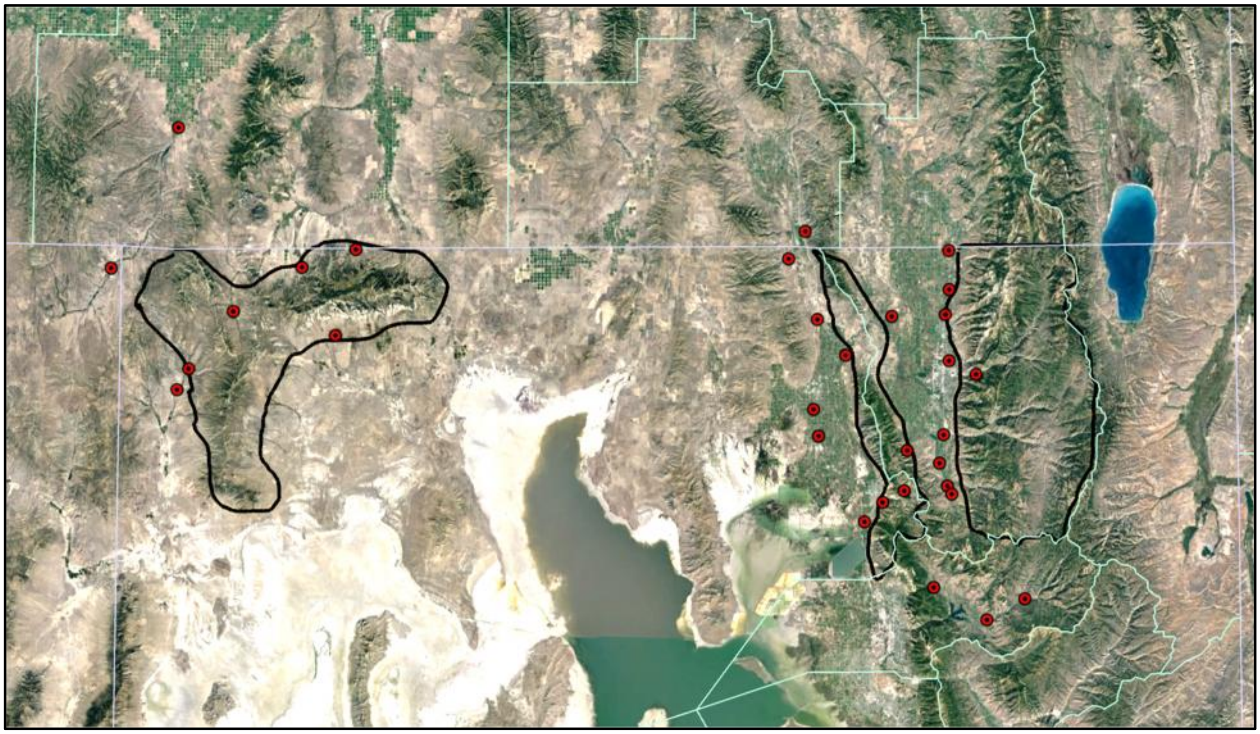


Figure 2.1 CNG sites and seeding target areas for the 2019-2020 Northern Utah Program

There were 31 available seeding generators located in Cache County, Box Elder County, and Weber County for seeding the target areas. Two CNGs were located on the Idaho side of the state line, one 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 sites for the generators involves studying topographical maps and identifying general areas most suitable, considering the typical wind flows and terrain effects during storm periods. Most generator sites are restricted to inhabited areas, since the 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 generators are situated to enable seeding operations in southwesterly, westerly, or northwesterly flow situations.

Table 2-1
Cloud Seeding Generator Sites

ID	Site Name	Elevation (ft)	Lat (N)	Long (W)
1-1	Oakley	4570	42⌈14.04'	113⌈53.55'
1-3	Yost	5986	41⌈57.40'	113⌈33.01'
1-4	Standrod	5811	41⌈59.61'	113⌈24.34'
1-5	Grouse Creek North	5484	41⌈45.08'	113⌈51.07'
1-6	Grouse Creek	5334	41⌈42.54'	113⌈52.94'
1-7	Trout Creek	5070	41⌈57.00'	114⌈04.00'
1-8	Lynn	5930	41⌈52.00'	113⌈44.00'
1-9	Rosette	5640	41⌈49.29'	113⌈27.49'
1-10	Malad South	4450	42⌈02.00’	112⌈12.00’
1-11	Portage	4500	41⌈58.71'	112⌈14.68'
1-12	Plymouth	4417	41⌈51.45'	112⌈10.09'
1-13	Collinston	4500	41⌈47.15'	112⌈05.58'
1-14	Tremonton	4295	41⌈40.69'	112⌈10.75'
1-15	Bear River City	4265	41⌈37.49'	112⌈09.96'
1-16	Brigham City	4690	41⌈29.54'	111⌈59.77'
1-17	Perry	4404	41⌈27.21'	112⌈02.67'
2-1	Cove	4577	41⌈59.65'	111⌈48.81'
2-2	Richmond	4600	41⌈54.96'	111⌈48.84'
2-3	Newton	4662	41⌈51.78'	111⌈58.12'
2-4	Smithfield	4694	41⌈51.96'	111⌈49.50'
2-5	Logan	4580	41⌈46.41’	111⌈48.94’
2-7	Wellsville	4884	41⌈35.72'	111⌈55.80'
2-8	Hyrum	4816	41⌈37.58'	111⌈49.92'
2-9	Paradise	4875	41⌈34.19'	111⌈50.62'
2-10	Mantua	5200	41⌈30.89'	111⌈56.34'
2-11	Avon	5059	41⌈31.45'	111⌈49.39'
2-12	Avon South	5079	41⌈30.47'	111⌈48.70'
3-3	Red Rock Ranch	5473	41⌈17.86'	111⌈37.17'
3-6	Huntsville	5066	41⌈15.37'	111⌈43.21'
3-7	Liberty	5107	41⌈19.31'	111⌈51.70'
3-8	Logan Canyon	4971	41⌈44.77'	111⌈44.72'

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. No suspensions were enacted for the Northern Utah seeding program during the 2019-2020 operational season.

3.0 WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

NAWC maintains a fully equipped project operations center at its Sandy, Utah headquarters. Meteorological information is acquired online from a wide variety of sources, including some subscriber services. This information includes weather forecast model data, surface observations, rawinsonde (weather balloon) upper-air observations, satellite images, radar information and weather cameras. This information helps NAWC meteorologists to determine when conditions are appropriate for cloud seeding. Figures 3.1 – 3.3 show examples of some of the available weather information that was used in this decision-making process during the 2019-2020 winter season. Of note in the February 16 event (Figures 3.1-3.2) is the large amount of mountain wave clouds seen in Figure 3.1, which are apparent from the "fish scale" patterns apparent in the clouds (white areas in the image). This can give the meteorologist valuable information regarding stability and wind patterns in the atmosphere. Figure 3.4 illustrates the predictions of ground-based seeding plume dispersion using the National Oceanic and Atmospheric Administration's HYSPLIT 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. NAWC's meteorologists are able to access all meteorological products from their homes, allowing continued monitoring and conduct of seeding operations outside of regular business hours.

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

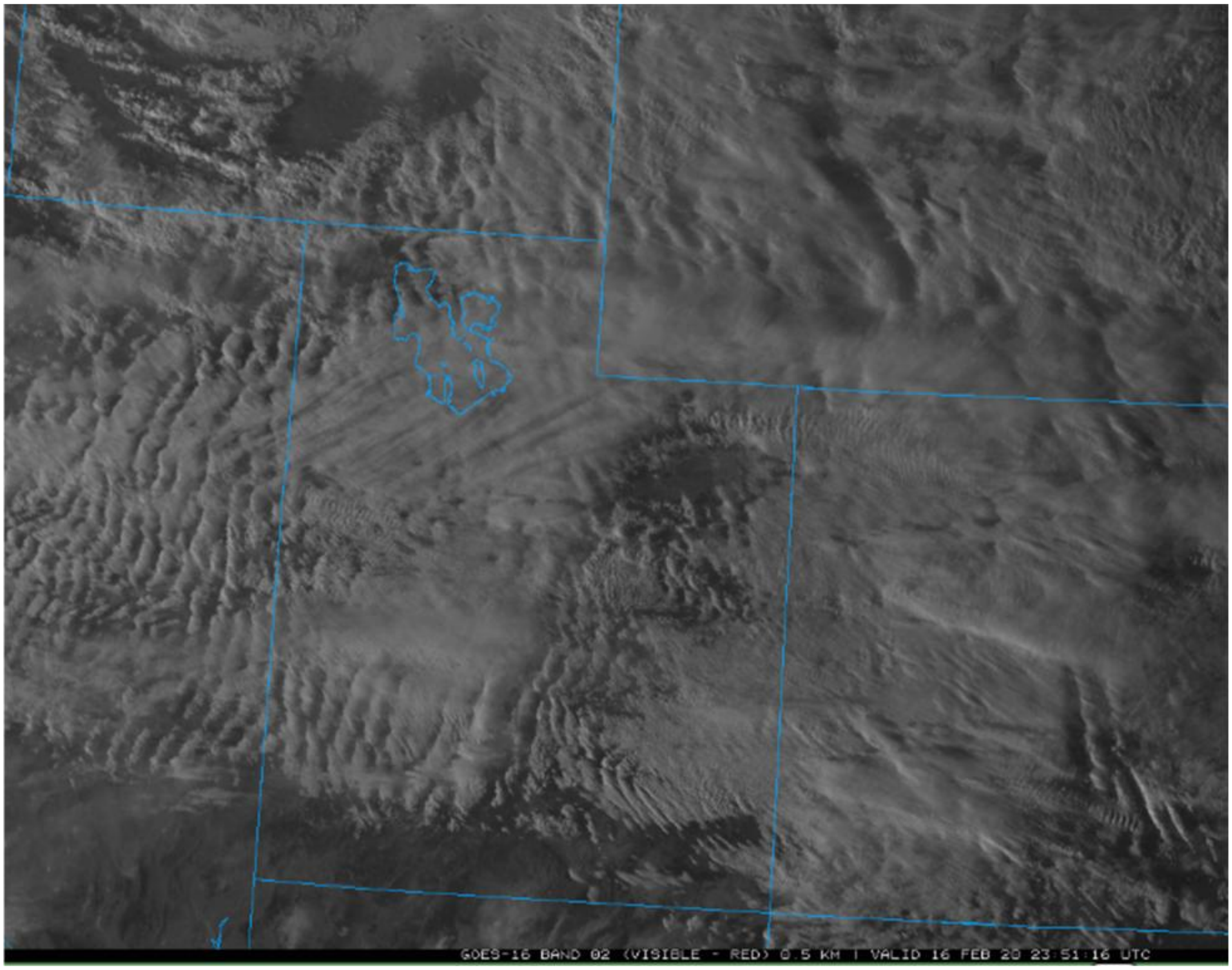


Figure 3.1 Visible spectrum satellite image during a storm event over Utah on February 16, 2020

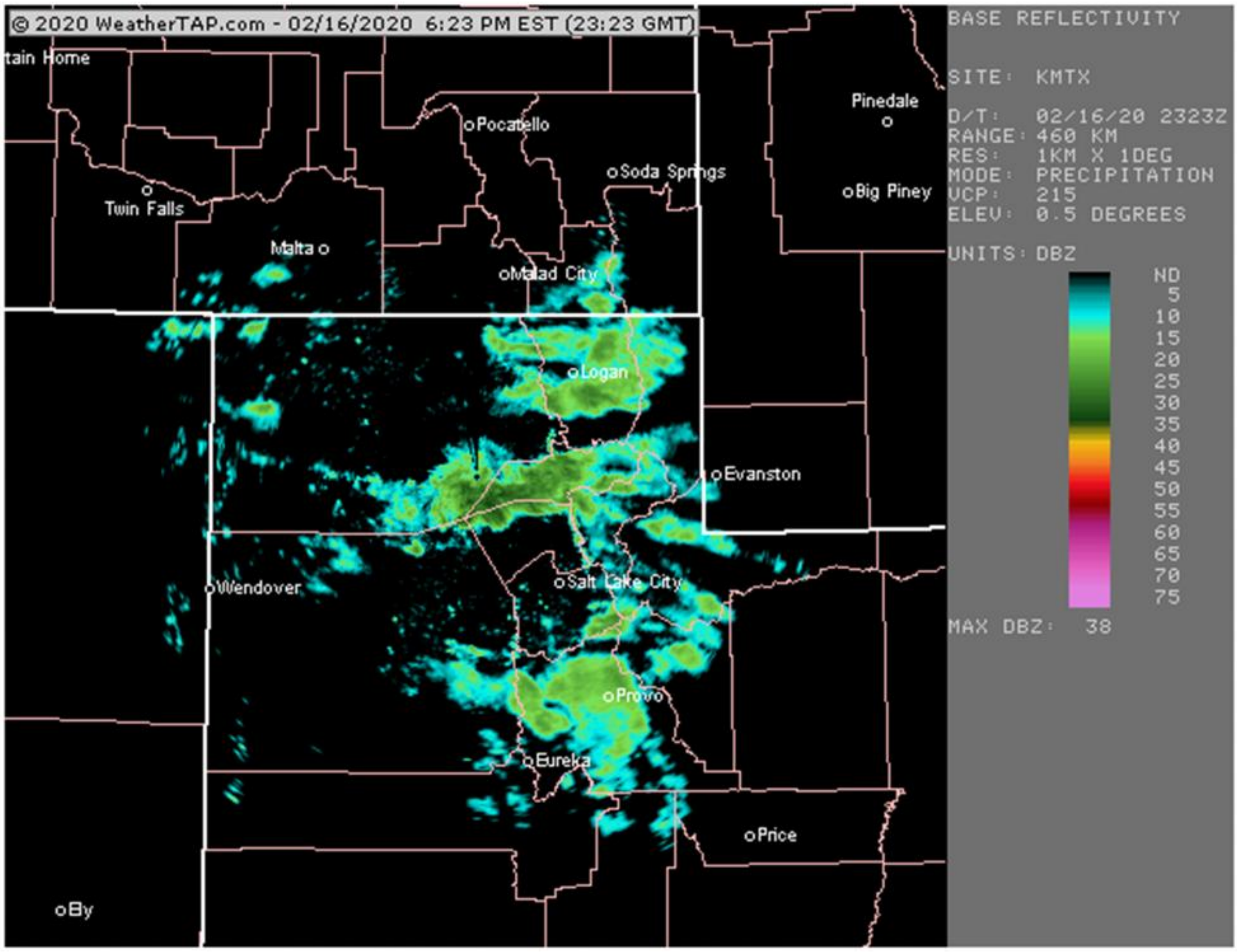


Figure 3.2 Weather radar image on the evening of February 16, 2020

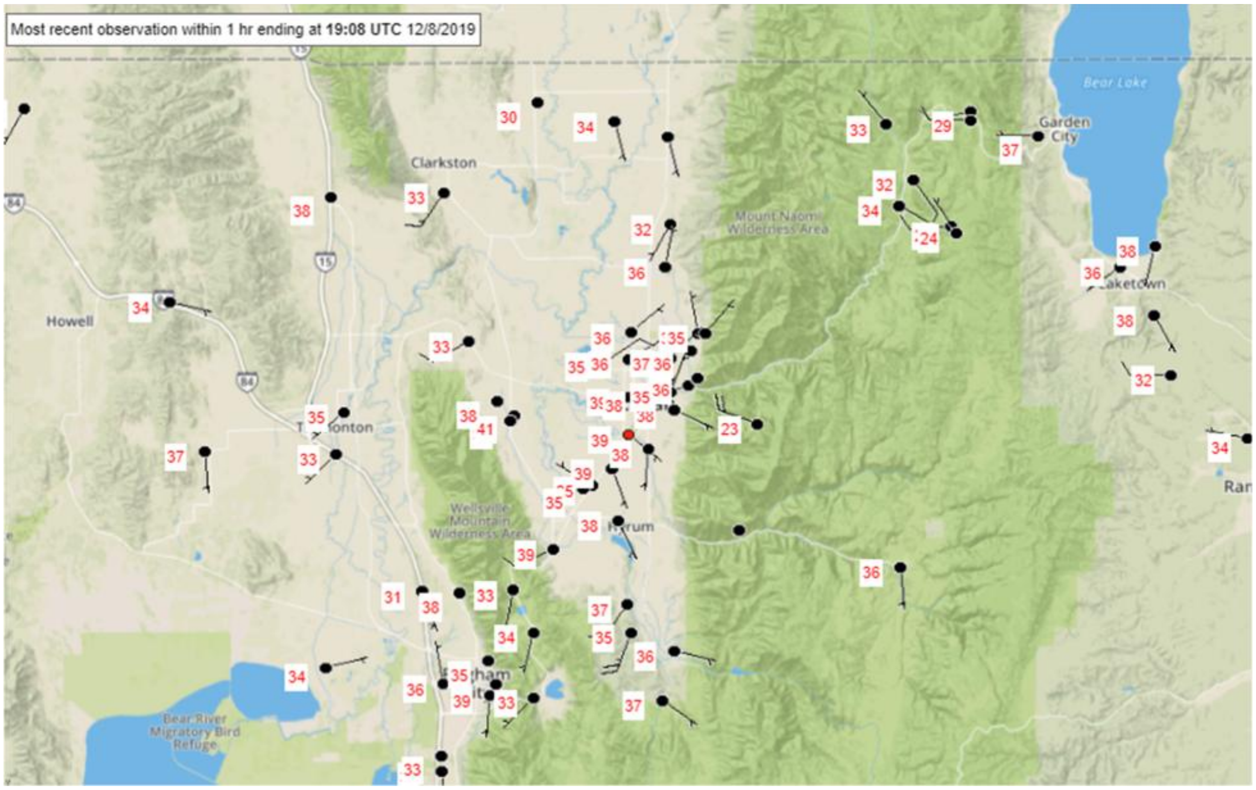


Figure 3.3 Mesowest surface data map on December 8, 2019. Surface observations are important for diagnosing low-level wind patterns and mixing.

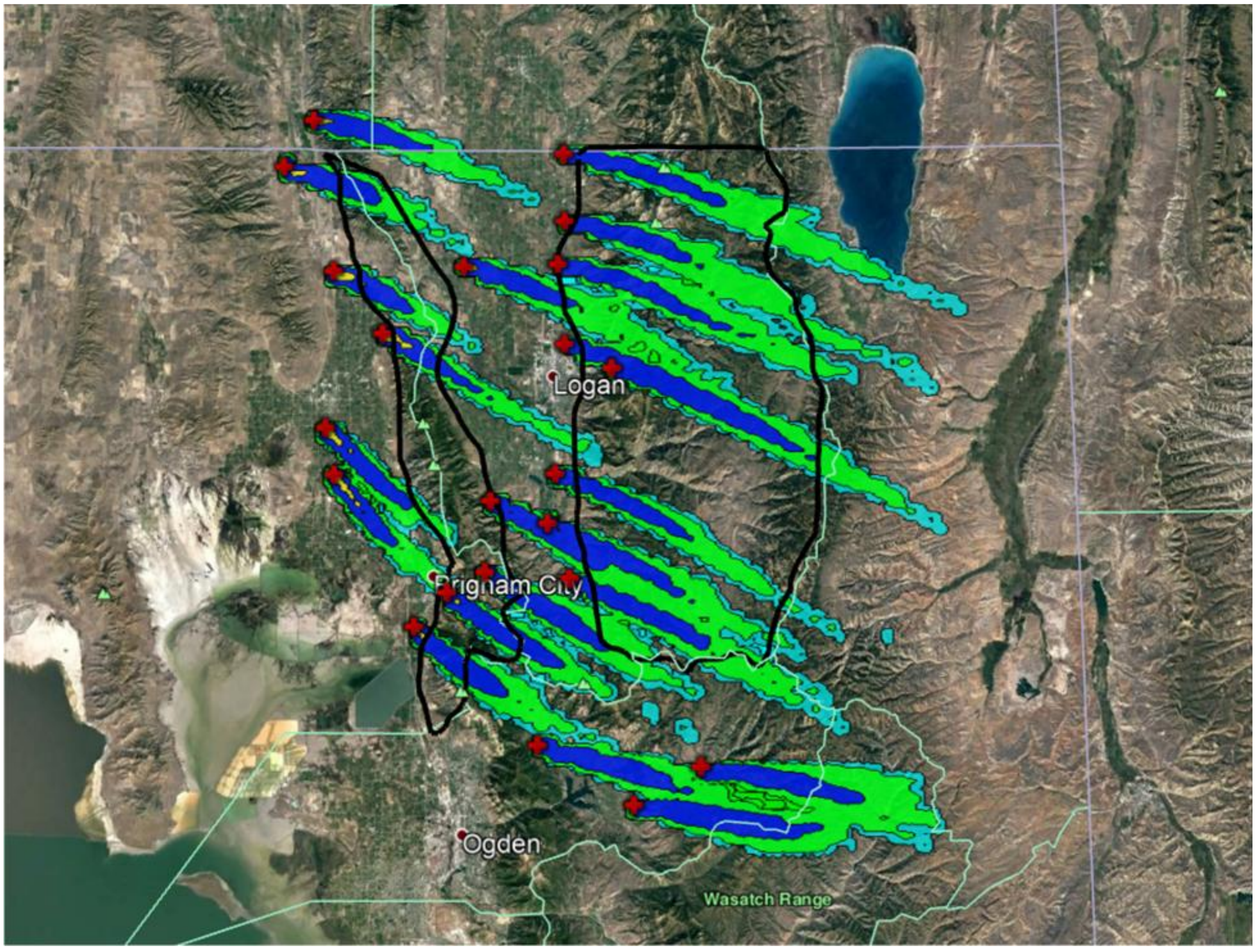
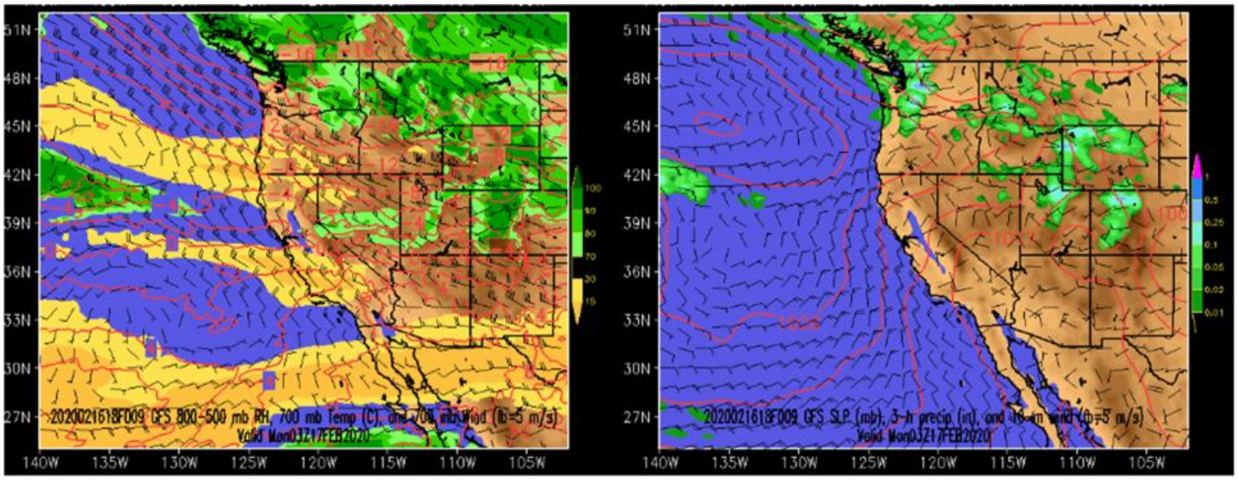


Figure 3.4 HYSPLIT plume dispersion forecast for a storm event on the night of February 16-17, 2020, for all potential seeding locations near the eastern portion of the program



Figures 3.5 GFS (Global Forecasts System) model plot during a storm event on February 17, 2020. These types of plots provide analyses and forecasts for things such as wind, temperatures, moisture at various levels of the atmosphere, as well as surface parameters such as accumulated precipitation.

4.0 OPERATIONS

The 2019-2020 seeding program in Box Elder and Cache Counties began on December 1, 2019 and ended on March 31, 2020. During the four-month season, there were 18 seeding operations conducted on portions of 28 days. Three storms were seeded in December, six in January, three in February (including one split between February and March), and six additional storms were seeded in March. A cumulative 1,797.5 hours of operations were conducted from all the generator sites during the season. 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.

Precipitation was near normal in northern Utah during the 2019-2020 winter season. Snowpack in the Bear River Basin on April 1, 2020 averaged 110% of normal (median), with about 94% of the normal (mean) water year precipitation to date. Figures 4.2 to 4.4 show snow water content and precipitation, compared to the long-term average values, at three target area SNOTEL sites: Bug Lake, Monte Cristo, and Tony Grove Lake, for the season. Figure 4.5 shows the Bear River Basin water year snow water content for this season, as well as average and maximum/minimum seasons.

Table 4-1
Storm Dates and Number of Generators Used,
2019-2020 Season

Storm No.	Date(s)	No. of Generators Used	No. of Hours
1	December 8-9	6	84.25
2	December 12-13	15	186.5
3	December 14	11	89.5
4	January 1-2	18	355.5
5	January 8	6	18.25
6	January 12-13	12	127.75
7	January 14	15	68.25
8	January 16-17	10	96
9	January 28-29	14	136.5
10	February 2-3	4	39
11	February 16-17	8	109.75
12	February 29 – March 1	1	10
13	March 14-15	1	22
14	March 18	5	19
15	March 21	3	9
16	March 24-25	20	352
17	March 30	5	12.75
18	March 31	8	61.5
Season Total	---	---	**1,797.5**

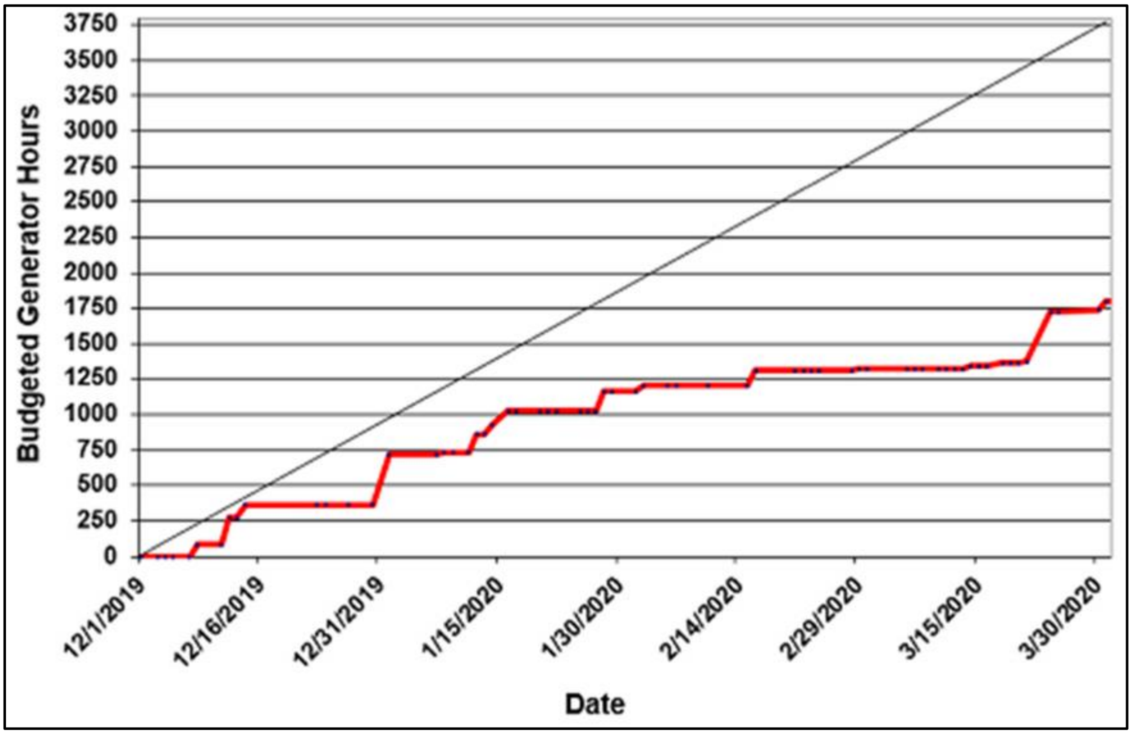


Figure 4.1 **Seeding operations during the 2019-2020 season (red), compared with a linear usage of total budgeted hours (diagonal black line).**

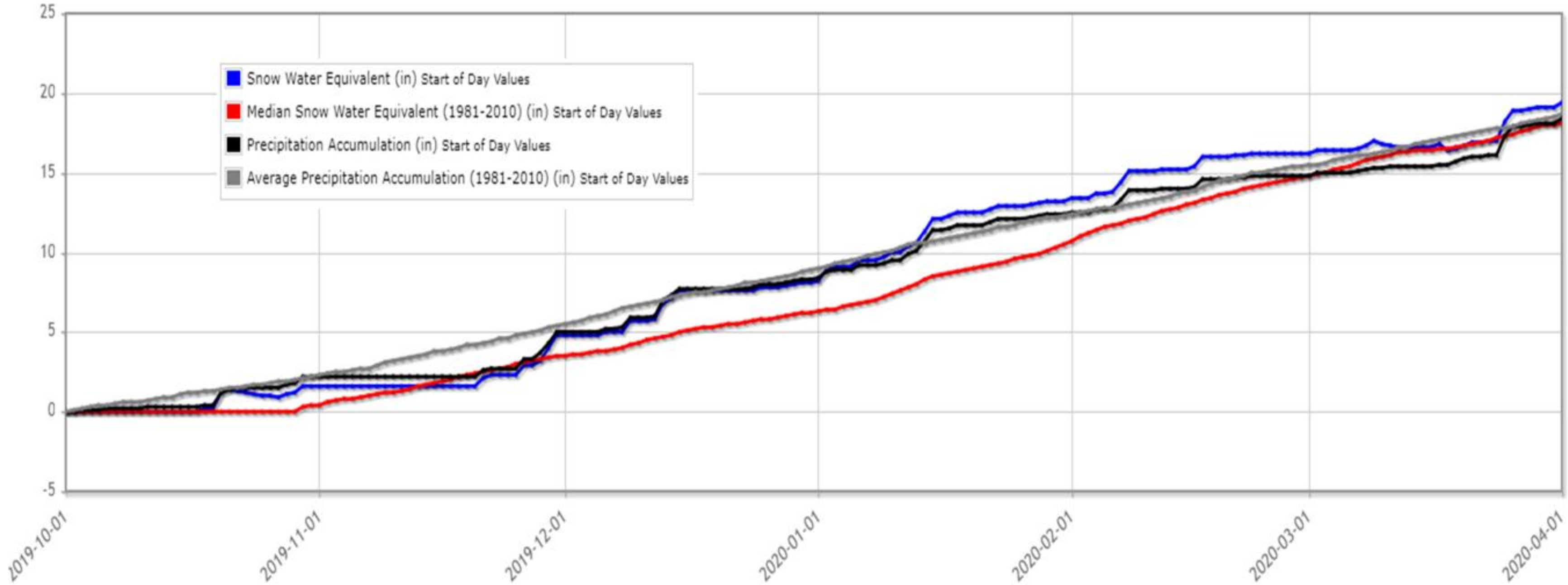


Figure 4.2 SNOTEL snow and precipitation plot for October 1, 2019 through April 1, 2020 for Bug Lake, UT. Smoothed lines are the corresponding normals.

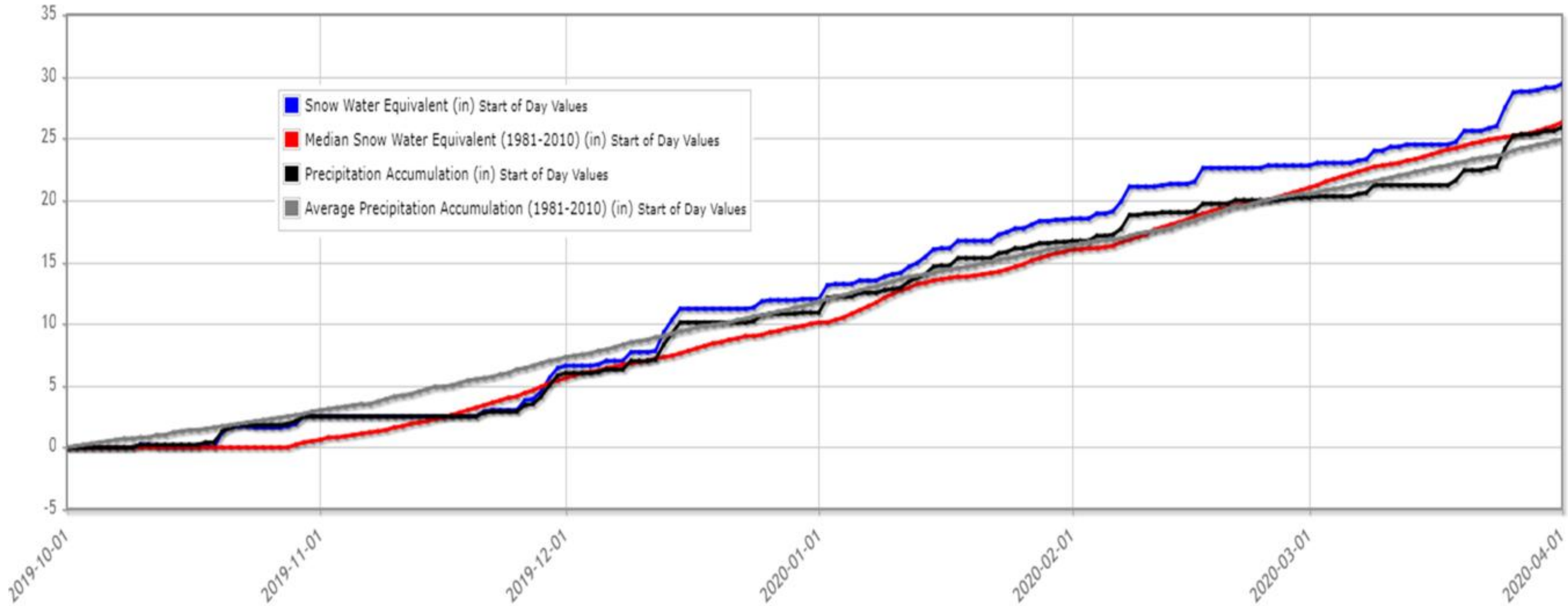


Figure 4.3 SNOTEL snow and precipitation plot for October 1, 2019 through April 1, 2020 for Monte Cristo, UT. Smoothed lines are the corresponding normals.

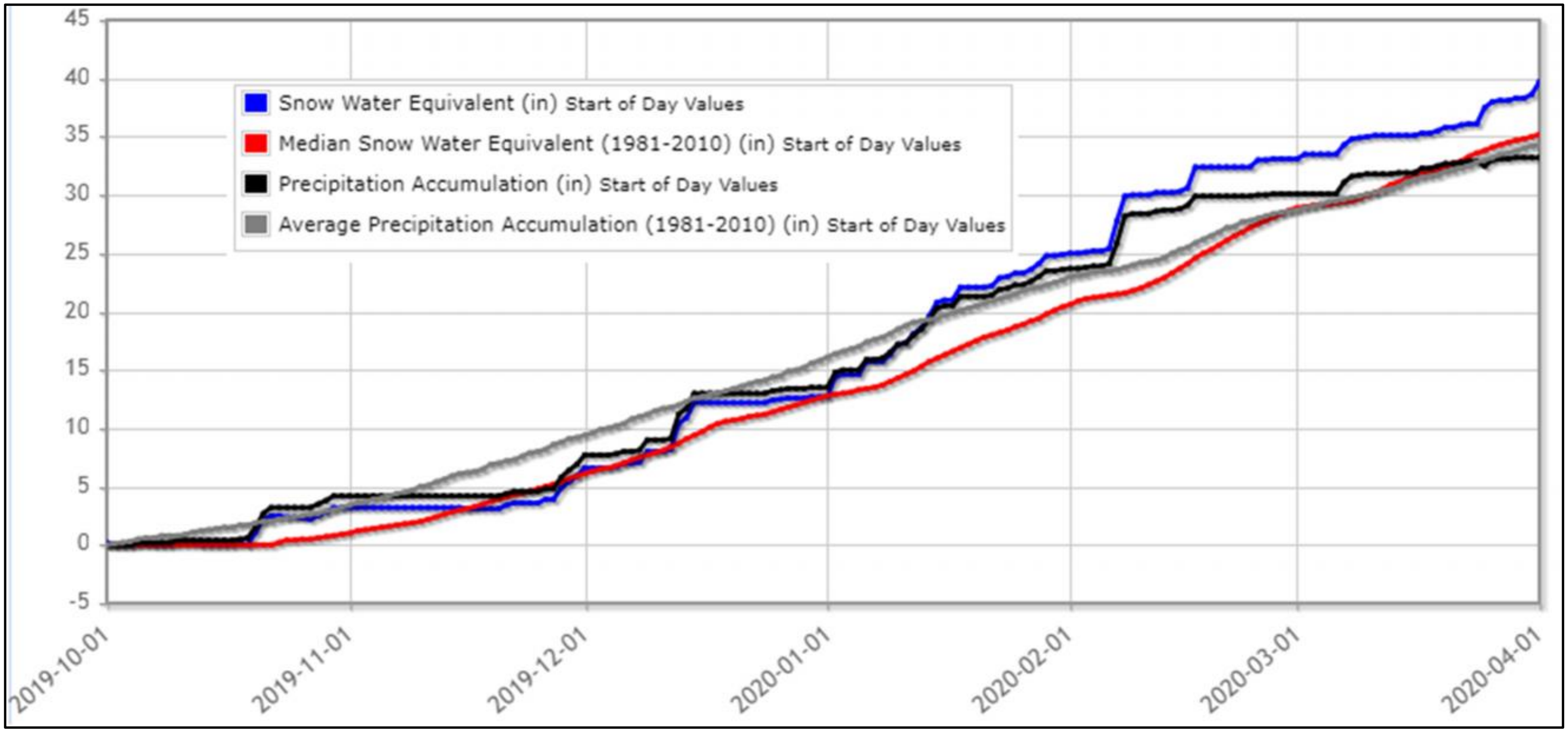


Figure 4.4 SNOTEL snow and precipitation plot for October 1, 2019 through April 1, 2020 for Tony Grove Lake, UT. Smoothed lines are the corresponding normals.

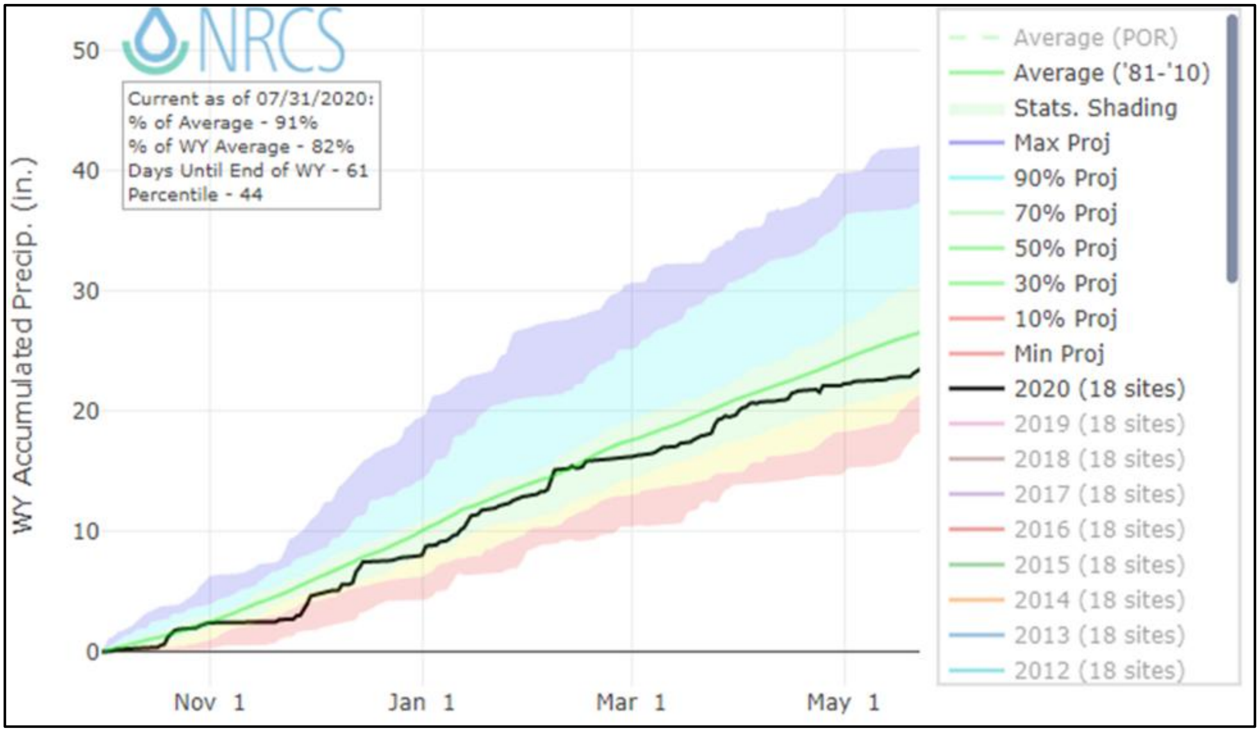


Figure 4.5 **SNOTEL accumulated precipitation plot (from NRCS) for the current water year, compared to average (green line) and max/min values, in the Bear River Basin; black line represents the 2020 water year through mid-May.**

4.1 Operational Procedures

During the operational period, the project meteorologist, with the aid of continually updated online weather information, monitored each approaching storm. 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 2019

December precipitation was somewhat below normal in northern Utah, with a total of three seeding opportunities, all during the first half of the month. Figure 4.6 shows the monthly precipitation totals around the region, as a percentage of the monthly normal (mean) values.

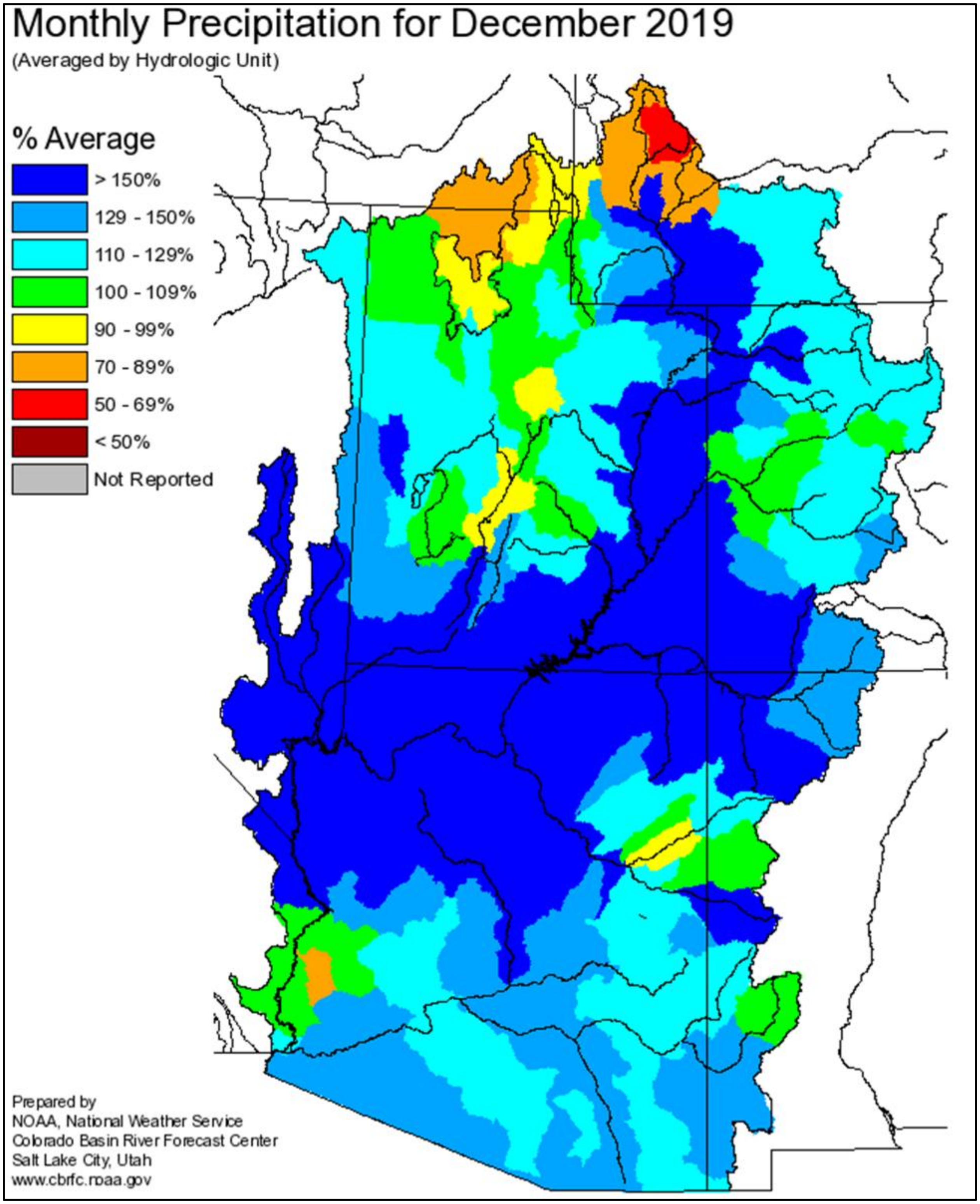


Figure 4.6 December 2019 precipitation, percent of normal

A weak frontal boundary moved into the area on December 8th, bringing a mix of rain and snow to lower elevations and light to moderate snow to the mountains. Although the temperature profile was too stable initially, conditions improved later in the day and seeding was conducted from the early evening hours and continued through the night in northwesterly flow for the eastern portions of the target area. Northwestern Box Elder County was essentially dry during this period. The 700-mb temperature was around -8°C, and precipitation totals ranged between 0.5 – 1.0 inches at SNOTEL sites in the seeded target areas.

A moist, nearly zonal (west to east) jet stream pattern had set up over the area on December 12th. Although the temperature profile was warm/stable at first, with precipitation mainly from a high cloud deck, conditions improved later in the day with cooling mid-level temperatures and precipitation becoming more convective in nature. Seeding was conducted for all target areas in west to northwest flow from the evening of December 12th into the morning of the 13th. Convective and orographic precipitation continued during this time, with some obvious orographic "streamers" of precipitation, initiated by terrain features, visible in radar imagery on the morning of December 13th. The 700-mb temperature was near to below -8°C during most of this time. This appeared to be an excellent seeding situation overall, and at least an inch to locally two inches of water equivalent was measured at SNOTEL sites. Seeding ended by mid-morning on the 13th as precipitation quickly ended over the area.

Another system, in a series, brought additional precipitation to the area from later on December 13th into the 14th. Although warm advection and precipitation from a higher cloud deck made conditions unfavorable initially, conditions had improved by early on December 14th with convective and orographic precipitation features apparent in radar imagery. Seeding was conducted for the eastern target areas during the daytime hours during west/northwest flow. Precipitation and seeding ending around late afternoon. The 700-mb temperature was near -8°C during this seeding period, with precipitation totals (for the storm event as a whole) ranging from over half an inch to locally over an inch in the target areas.

January 2020

January brought generally near to slightly above average precipitation to northern portions of Utah, with an active storm track during most of the month. This active storm pattern also helped to keep the lower levels mixed, with only limited duration inversions able to become established in the valleys. Figure 4.7 shows the January precipitation patterns, as a percent of average, around the region. There were a total of six seeded storm periods in January.

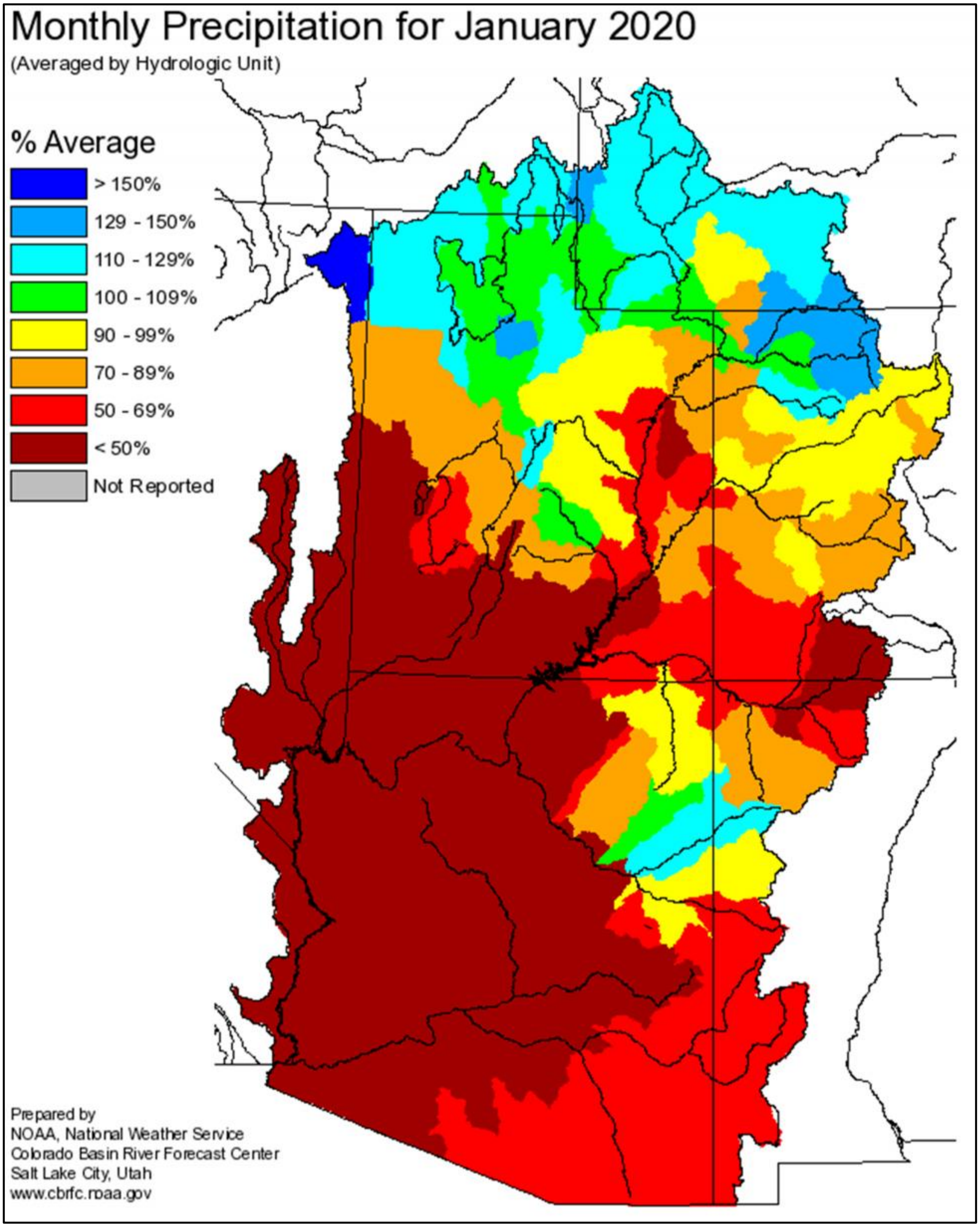


Figure 4.7 January 2020 precipitation, percent of normal

A storm event began over northern Utah on January 1st. Although the temperature profile was too stable for seeding at first, cold air advection began after midday and there were convective elements that developed as well. Seeding began for all areas during the early afternoon, as low level mixing improved with winds from the southwest at lower levels and northwest aloft. Although there was a brief break in storm activity during the evening hours, more developed overnight (January 1st-2nd) and seeding continued as the 700 mb temperature dropped to below -10°C overnight. Radar showed a good deal of orographic (mountain – induced) snowfall over the Wasatch Range, which indicates a favorable situation for seeding operations. Some light orographic precipitation continued on January 2nd, and seeding continued for eastern portions of the target through midday, ending during the early afternoon hours. Precipitation totals of between about 0.6 to 1.6 inches of water equivalent were observed in most target areas with this event.

A weak system on January 8th brought a brief seeding opportunity to eastern portions of the area. Although the temperature profile was stable at first, with a higher cloud deck, mixing improved after midday and some weak orographic snow showers were noted in a lower cloud deck that was based near to below crest level of the northern Wasatch. Seeding was conducted for a few hours in the afternoon in westerly to northwesterly flow, with a 700 mb temperature around -10°C to -11°C. Precipitation totals were mostly light with this event, generally ranging from around 0.2 to 0.5 of an inch of water equivalent.

A storm system crossed the area on the night of January 12th-13th, with a fairly cold air mass over the area. The 700 mb temperature was around -12°C to -15°C overnight, with winds shifting from the southwest to the west. Seeding was initiated late in the evening (12th) for eastern areas and conducted overnight, ending on the morning of the 13th as 700 mb temperatures were below -15°C and any SLW appeared to be very limited. Precipitation totals during this storm period were generally light, around a quarter inch of water content in most areas.

Another storm in a series brought a seeding opportunity area-wide, with seeding beginning during the morning to early afternoon hours of January 14th. The 700 mb temperature was around -12°C to -14°C in a strong westerly wind pattern. A cold frontal snow band quickly moved across the area, with snow and seeding ending around midday in northwestern Box Elder County and a couple of hours later for eastern portions. Precipitation totals during this storm period ranged from around 0.5 inch of water content at many SNOTEL sites to well over an inch in some orographically favored areas.

A fast-moving frontal system with very strong winds arrived during the night of January 16th-17th, with seeding beginning during the night and continuing through the morning of the 17th. Temperatures were suitably cold, falling to about -14°C by midday on the 17th. Snowfall was orographic in nature and highly variable with this event, ranging up to around an inch of water in some portions of the northern Wasatch (eastern target areas) and very little in some other areas such as northwestern Box Elder County.

Although some weather systems crossed the area during the January 21st-24th period, conditions were unfavorable for seeding with a stable temperature profile and/or unfavorable cloud types. However, a much more favorable situation developed on January 28th, with a frontal system bringing some convective-type precipitation and good mixing in the lower levels. Seeding was conducted on the evening of the 28th in northwest Box Elder County, ending late there but continuing overnight for eastern portions. The 700 mb temperature cooled to near/below -8°C overnight following the cold frontal passage. Seeding ended with drying conditions on the morning of January 29. Precipitation totals were quite variable, ranging from only about 0.1 inches at some SNOTEL sites to locally over a half inch at some locations.

February 2020

The weather was quite dry over most of the region during February (Figure 4.8). Much of the precipitation that did occur in the northern Utah mountains were from a February 6th-7th event that unfortunately was not favorable for seeding. However, there were three seeded storm periods during the month.

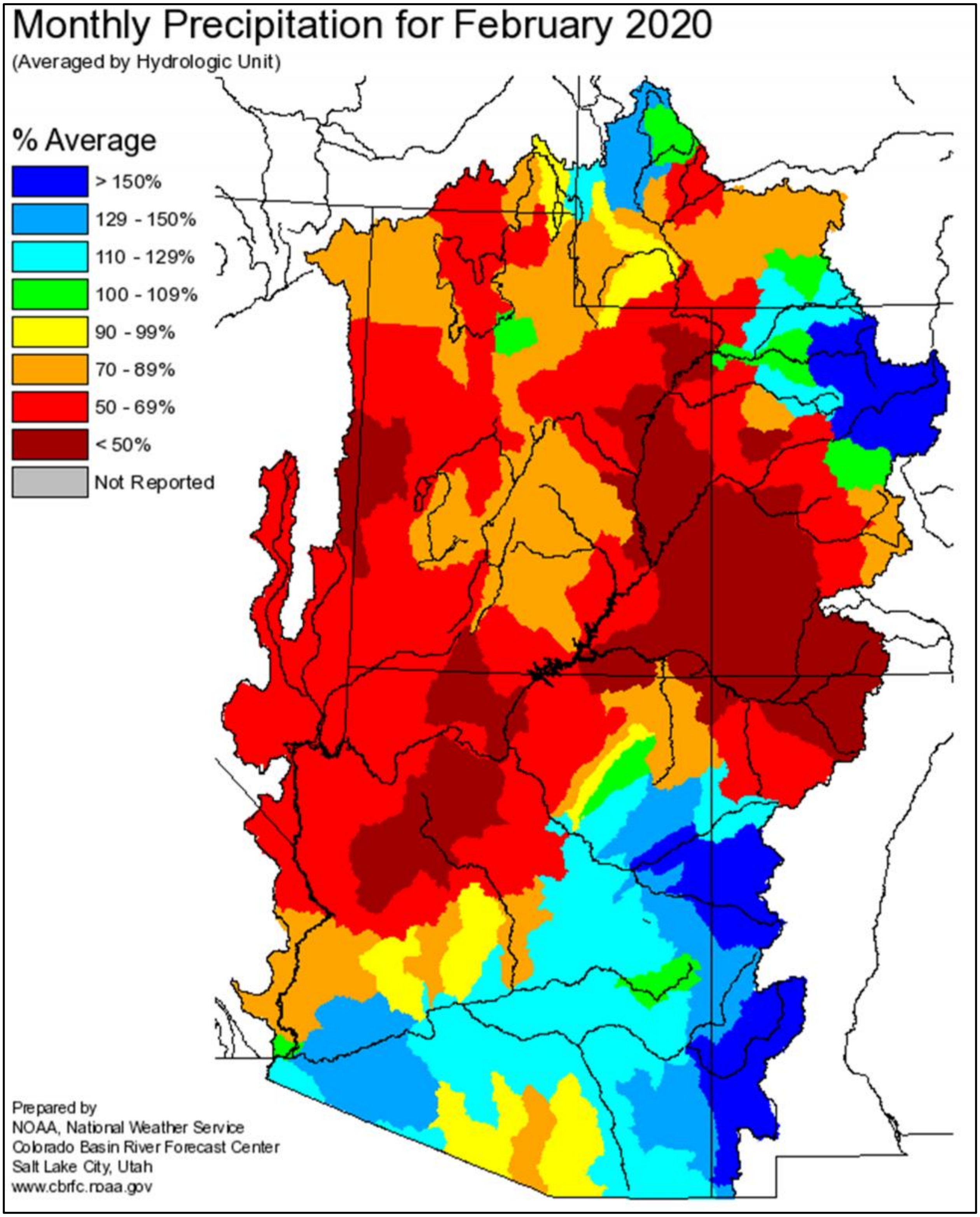


Figure 4.8 February 2020 precipitation, percent of normal

A very cold trough over the northwestern U.S. on February 2nd resulted in a transition from very mild temperatures (near 0°C at 700 mb) on the 2nd to very cold temperatures (as low as -20°C at 700 mb) on the 3rd. In between these two air masses, was a cold front that crossed northern Utah on the night of February 2nd-3rd. Although SLW appeared very limited and the low-level air mass was generally lacking moisture within the frontal zone, seeding was conducted from several sites for eastern target areas overnight in anticipation of at least a briefly favorable period. Seeding ended early on the 3rd even as light snowfall continued over the area, as temperatures were very cold and there was a clear lack of liquid water to seed. Precipitation totals at target area SNOTEL sites ranged from about 0.1 to 0.5" of water content with this event.

A ridge of high pressure along the west coast directed a moisture plume across far northern Utah on February 6th-7th, bringing strong northwesterly winds aloft and significant snowfall to orographically favored mountains of northern Utah. While this precipitation period was not seedable due to stable low-level temperatures and unfavorable cloud types, it did bring locally very significant moisture totals to the northern Wasatch Range. Some SNOTEL sites received as much as 3-4" of precipitation, while many others had totals in the 1-2" range.

A frontal system brought favorable seeding conditions for eastern portions of the target area beginning on the evening of February 16th and continuing overnight. The 700 mb temperature fell from about -7°C to -13°C during this period, with some convective and orographic precipitation types affecting eastern portions of the target area. Precipitation totals at SNOTEL sites were variable, under an inch in most areas but with some locally higher totals in the far north/east. Seeding operations ended early on the 17th as skies had mostly cleared.

A frontal boundary moved into far northern Utah on the night of February 29th – March 1st. Although conditions were somewhat marginal, seeding was conducted overnight to affect the northwest Box Elder County target area. Although most snowfall appeared to be from a higher cloud deck with limited liquid water, the 700 mb temperature cooled to around -10°C overnight and was therefore in a favorable range. Seeding ended early on March 1st as snowfall had essentially ended. Most SNOTEL sites (which are located in eastern target areas) had light amounts of about a quarter inch of water content, including the one SNOTEL site in northwestern Box Elder County with a 0.2 inch total.

March 2020

Precipitation totals were somewhat variable, generally below normal (northwest) to near or slightly above normal (eastern portions) in March, shown in Figure 4.9. While the first half of March was quite dry, there were some significant storm events during the second half of the month, producing a total of six seeding opportunities.

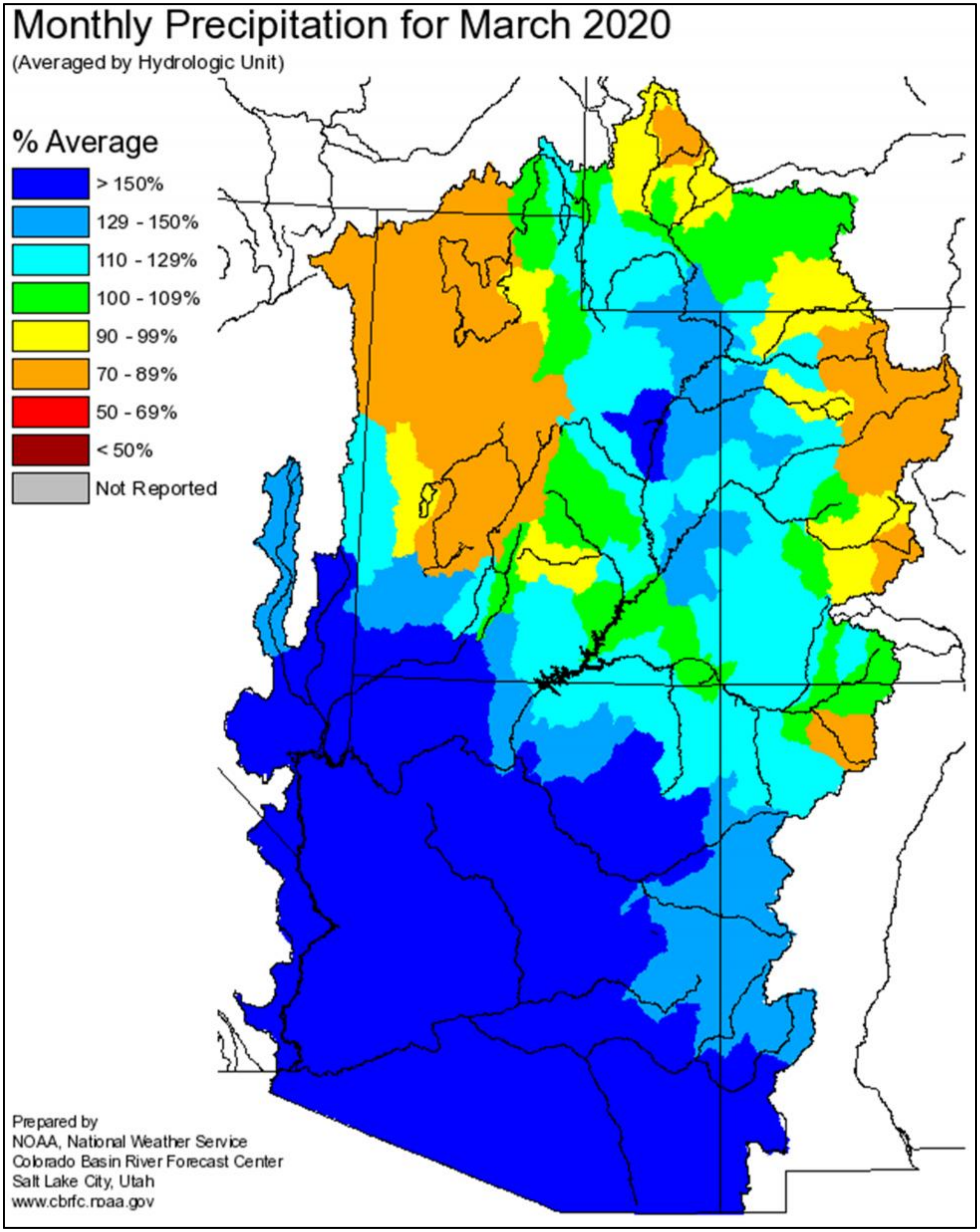


Figure 4.9 March 2020 precipitation, percent of normal

A storm system affected mainly far northwestern Utah on March 14th-15th. Although temperatures were on the warm side (around -4°C at 700 mb), southerly winds were favorable for using one site on the southern side of the main barrier in northwest Box Elder County. Seeding was conducted from midday on the 14th through the morning of the 15th at this location, with precipitation of a convective and orographic type in that area. The one SNOTEL site in that target area recorded a total of 1.5 inch of water content during this storm period, with generally zero to very light amounts in eastern portions of the target area where there was no seeding opportunity in this case.

A complex trough over the western U.S. on March 18th brought some brief seeding opportunity to eastern portions of the target area during the late morning to early afternoon hours. Precipitation was scattered, with winds mostly from the south to southwest and a 700 mb temperature around -5°C to -6°C. Precipitation totals were around 0.25 inches at most SNOTEL sites.

A brief seeding opportunity occurred on the afternoon of March 21st, with a weak trough and daytime heating helping the development of some convective showers across the area. Seeding was only conducted from a few sites for a few hours duration, with a 700 mb temperature around -7°C to -9°C and limited precipitation totals (mostly around 0.1 inch).

A major storm event affected mainly eastern portions of the target area on March 24th-25th, although seeding was conducted for all areas beginning on the 24th. A slow-moving cold front crossed the area late on March 24th through early on the 25th, with widespread precipitation as well as convective showers and thundershowers. Winds shifted from southwesterly on the 24th to light westerly on the 25th, with the 700 mb temperature ranging from -5°C to -10°C during the event. Precipitation was particularly widespread across eastern portions overnight (March 24th-25th), with convective showers persisting over eastern areas into the morning of the 25th. Overall, seeding was conducted for various portions of the target between midday on the 24th and midday on the 25th, and precipitation totals generally ranged from 1-2 inches of water equivalent at SNOTEL sites in eastern portions. This one of the most heavily seeded events of the season, with conditions appearing good to excellent during much of the period.

Some weak systems produced light and scattered (mainly diurnal, or daytime) showers across the area on March 28th -30th, with seeding conducted briefly during the early afternoon of March 30th as showers appeared somewhat more vigorous across the eastern target areas. The 700 mb temperature was around -5°C, which is in a favorable range considering the convective activity. Several SNOTEL sites recorded around 0.3 inches of water content on this day.

A deep trough centered over the Pacific Northwest resulted in a somewhat moist southwesterly flow across northern Utah on March 31st. Temperatures were on the warm side, around -5°C at 700 mb, but precipitation was orographic in nature (a positive factor) and appeared to have potential for seeding operations. Seeding was conducted during the morning and early afternoon, ending later in the day as the air mass became quite dry. Precipitation totals were highly variable and generally based on orographic effects, ranging from very light in some areas to close to an inch at some far northern sites.

5.0 ASSESSMENT OF SEEDING EFFECTS

5.1 Background

The seemingly simple issue of determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program is often a rather difficult task, especially when considering single-season results, and these should be viewed with appropriate caution. The primary reason for this difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area. 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, based on evaluating 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, e.g., precipitation, in both the target and control areas are taken from a period that has not been subject to cloud seeding activities, since past seeding could affect the development of a relationship between the target and control areas. These two sets of data are analyzed mathematically to develop a regression equation which estimates (calculates) the most probable amount of natural target area precipitation, based on the amount of precipitation observed in the control area. This equation is then used during the seeded period to estimate what the target area precipitation should have been in the absence of cloud seeding. A comparison can then be made between the estimated natural target area precipitation and that which 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 contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, correlations of 0.90 or better are considered excellent and correlations around 0.85 are good. A correlation of 0.90 indicates that over 80 percent of the variance (random variability) in the historical data set is explained by the regression equation. Correlations less than about 0.80 are still acceptable, but it would likely take much longer (many more years of comparison) to attach any statistical significance to the apparent seeding results.

5.2 General Considerations in the Development of Target/Control Evaluations

With the establishment of the Natural Resources Conservation Service's (NRCS) SNOTEL automated data acquisition system in the late 1970's, access to precipitation and 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. This 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.

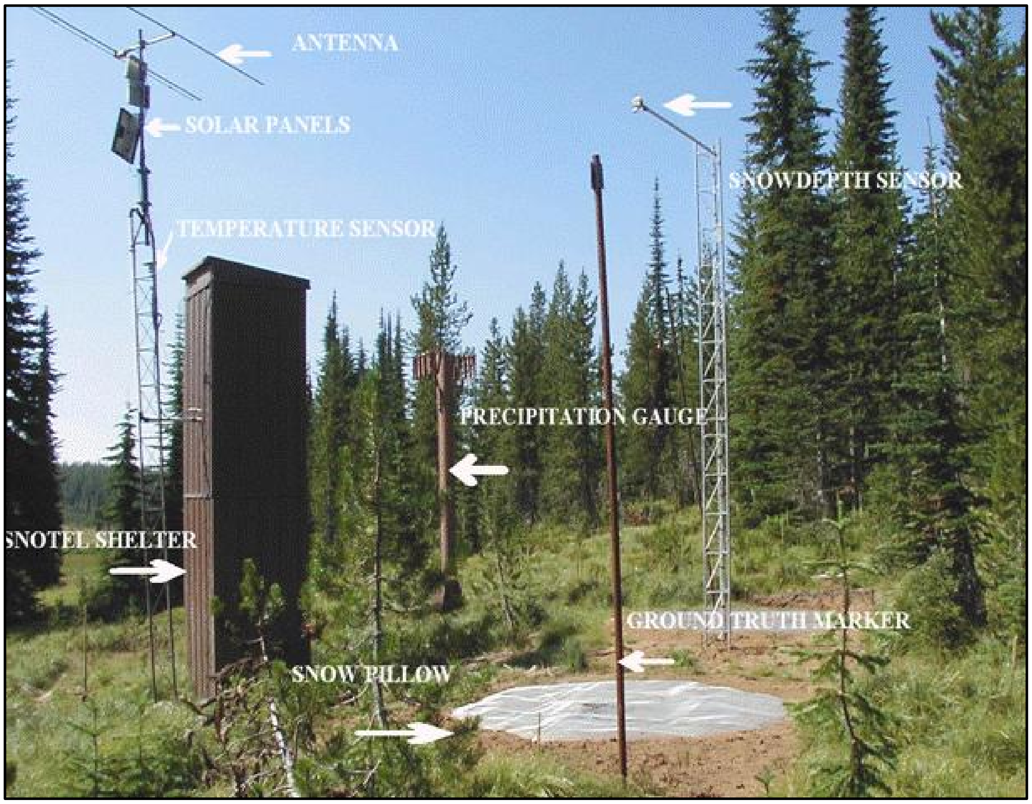


Figure 5.1 SNOTEL site photo

There have been, and continue to be, multiple cloud seeding programs conducted in the State of Utah. As a consequence, potential control areas that are unaffected by cloud seeding are somewhat limited. This is complicated by the fact that the best correlated control sites are generally those closest to the target area, and most measurement sites in this part of the state have been subjected to 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 is a consideration especially when selecting control sites. Some earlier weather modification research programs have indicated that the precipitation can be affected in areas downwind of the intended target areas. Analyses of some of these programs have indicated increases in precipitation in these downwind areas out to distances of 50-100 miles. Thus, control sites for evaluation of the 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 we have observed that some winter seasons are dominated by a particular upper airflow pattern while other seasons are dominated by other flow patterns. These different upper airflow patterns and resultant storm tracks often result in heavier precipitation in one area versus the other. For example, a strong El Nino pattern may favor the production of heavy winter precipitation in 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. Fortunately, missing data (typically on a daily basis) are noted in the historical database so that sites can be excluded from consideration if they have much missing data. A site would be excluded if it has significant amounts of missing data. If a significant measurement site move (more than a mile or change in elevation of 100-200 feet) is indicated in the station records, this may also be a factor. The double-mass plot, an engineering tool, will indicate any systematic changes in relationships between the two stations. If changes shown as inflections in the slope of the line connecting the points are significant, a site(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 is the excess, which may be the result of the seeding. Statistical tests have shown that such increases have very little statistical significance for an individual season, and usually fall within one standard deviation of the natural variability. However, an excess obtained by averaging the results of several seeded seasons is much more meaningful.

5.3 Evaluation of Precipitation 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.

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 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 actually 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.

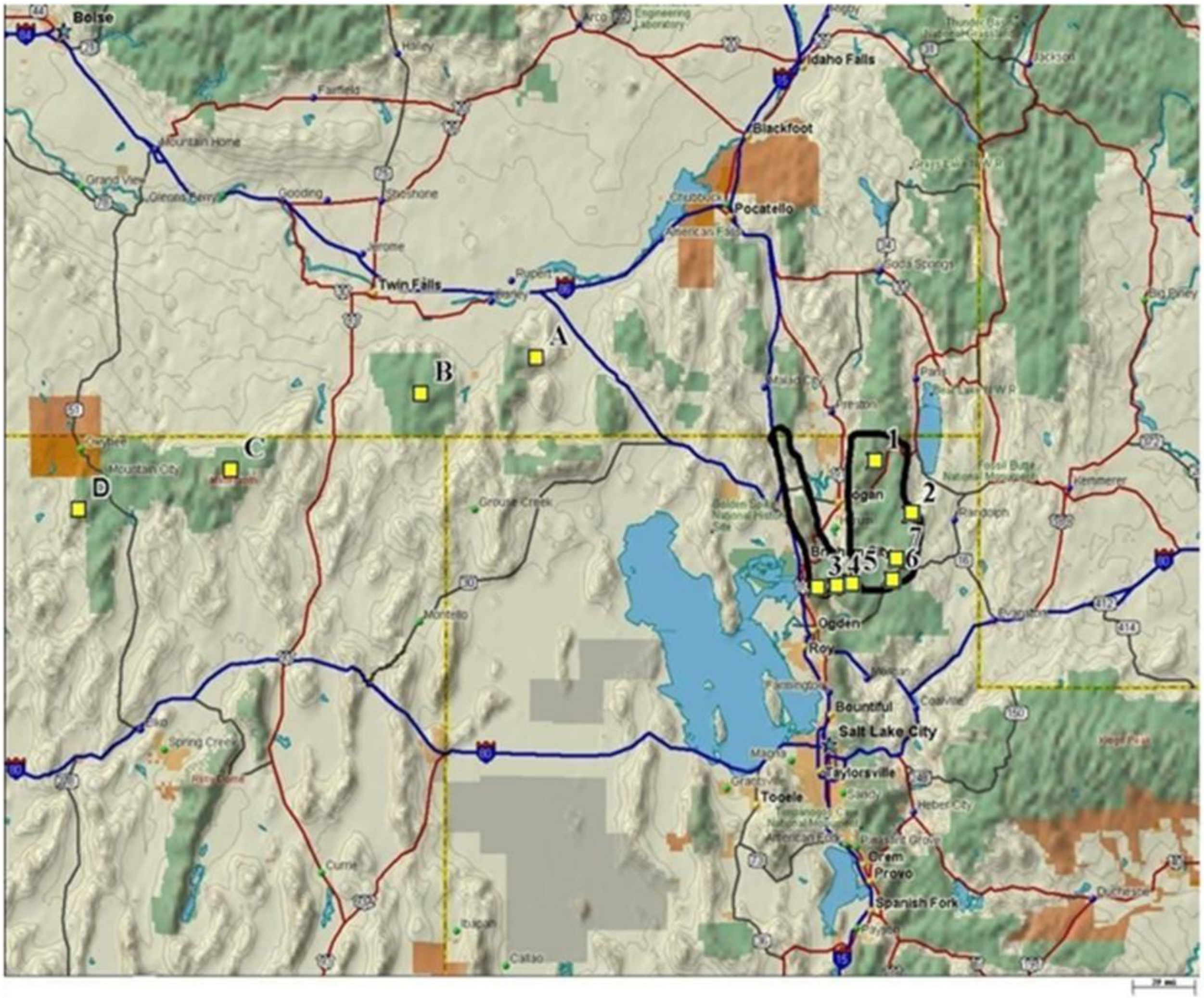


Figure 5.2 **Precipitation gauge sites used in evaluation, eastern Box Elder and Cache Counties, with site data in Table 4-1. The target area is outlined in black. The target sites are numbered; the control sites have letter ID's.**

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:

$$Y_C = 0.33 + 1.27(X_0) \qquad (1)$$

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:

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

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 15.20 inches for the December 2019 through March 2020 period was inserted in equation (1), the most probable average target area natural precipitation was calculated to be 19.60 inches using the linear regression technique. The average observed precipitation for the seven gauges in the target group was 17.77 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,

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

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:

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

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 0.91, or from (4), 9% less than that predicted using the regression equation. 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 4-site control group, are combined for the 31 seeded December-March periods (1989-2020 water years, excluding water year 2017 due to seeding suspensions and anomalous precipitation patterns as described in the 2017 report), **the indicated average increase in the eastern Box Elder/Cache County target area is 6%. The seasonal (December-March) difference between the observed and calculated precipitation is an area-wide average of over 1.0 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 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 50 water years, with the 19 water years from 1970 through 1988 representing the historical (unseeded) years and the remaining 31 years (1989 – 2019, 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.

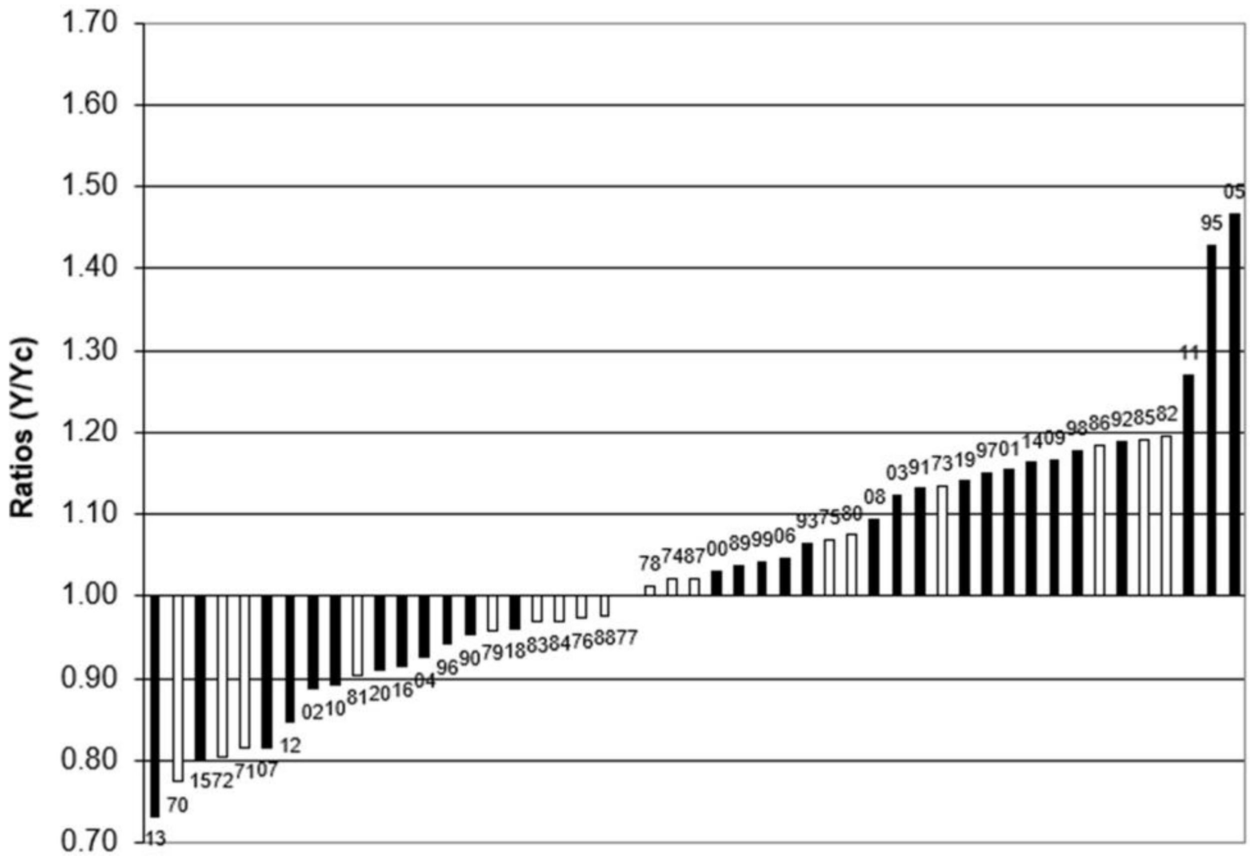


Figure 5.3 Calculated ratios for 1970-2020 December – March precipitation, Eastern Box Elder/Cache County Program, using the linear regression technique; White bars represent the historical, unseeded years and black bars the seeded years.

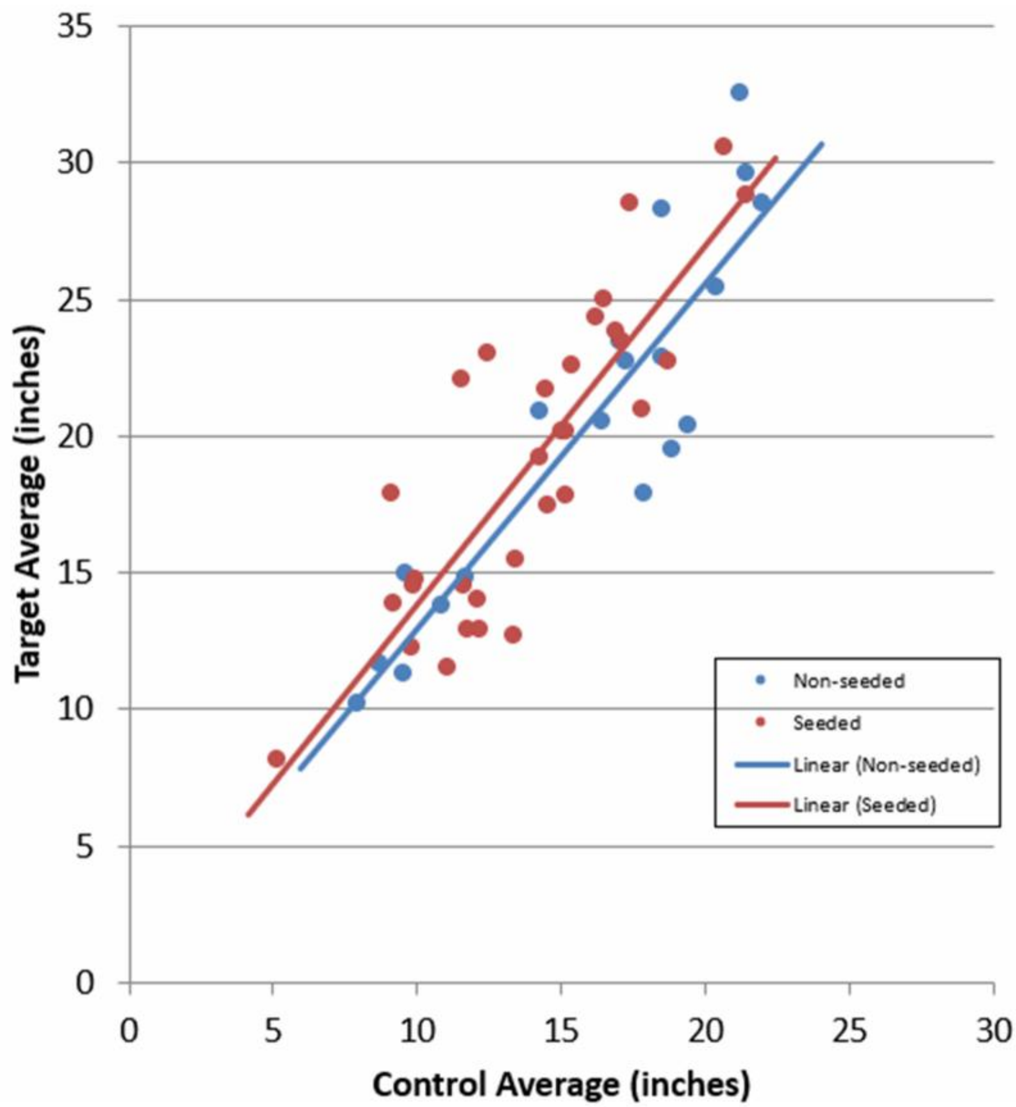


Figure 5.4 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for eastern Box Elder and Cache County precipitation linear regression

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; each new season is added to the sum of all of the previous seasons. In each figure, a line has been drawn through the points during the not-seeded base period. The plots show stable linear relationships prior to the beginning of cloud seeding. For comparison with the seeded period, the line describing the not-seeded period is extended at a constant slope through the seeded period.

The 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.

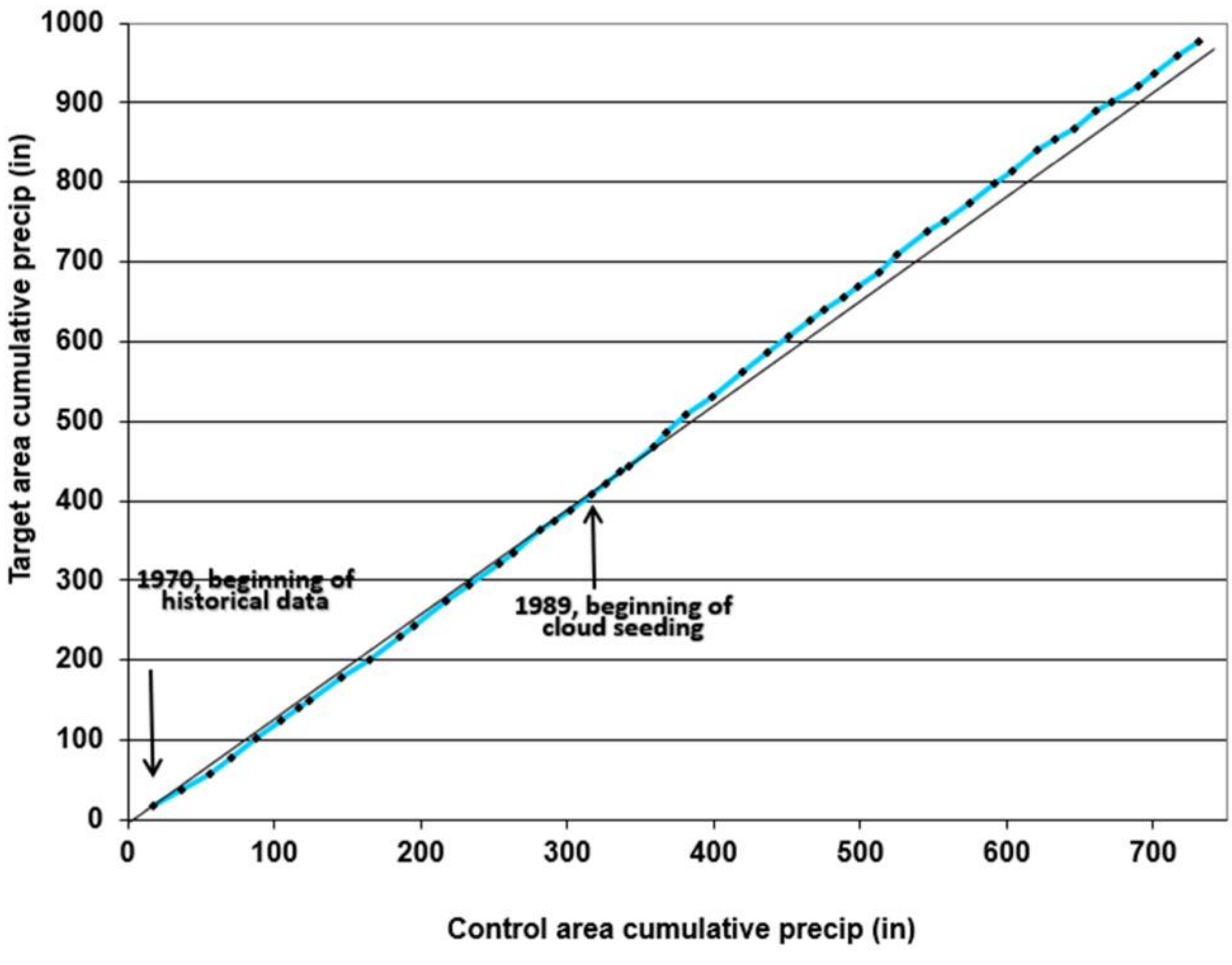


Figure 5.5 Double mass plot showing cumulative Dec-Mar <u>precipitation</u> for eastern Box Elder and Cache County target and control areas, water years 1970-2020.

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. **The resulting multiple linear regression ratio for this season is 0.95 with a ratio of 1.07 for the 31 seeded seasons of data, suggesting an average of 1.2 inches of increased water per season (fairly similar to that of the 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 near 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. 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.

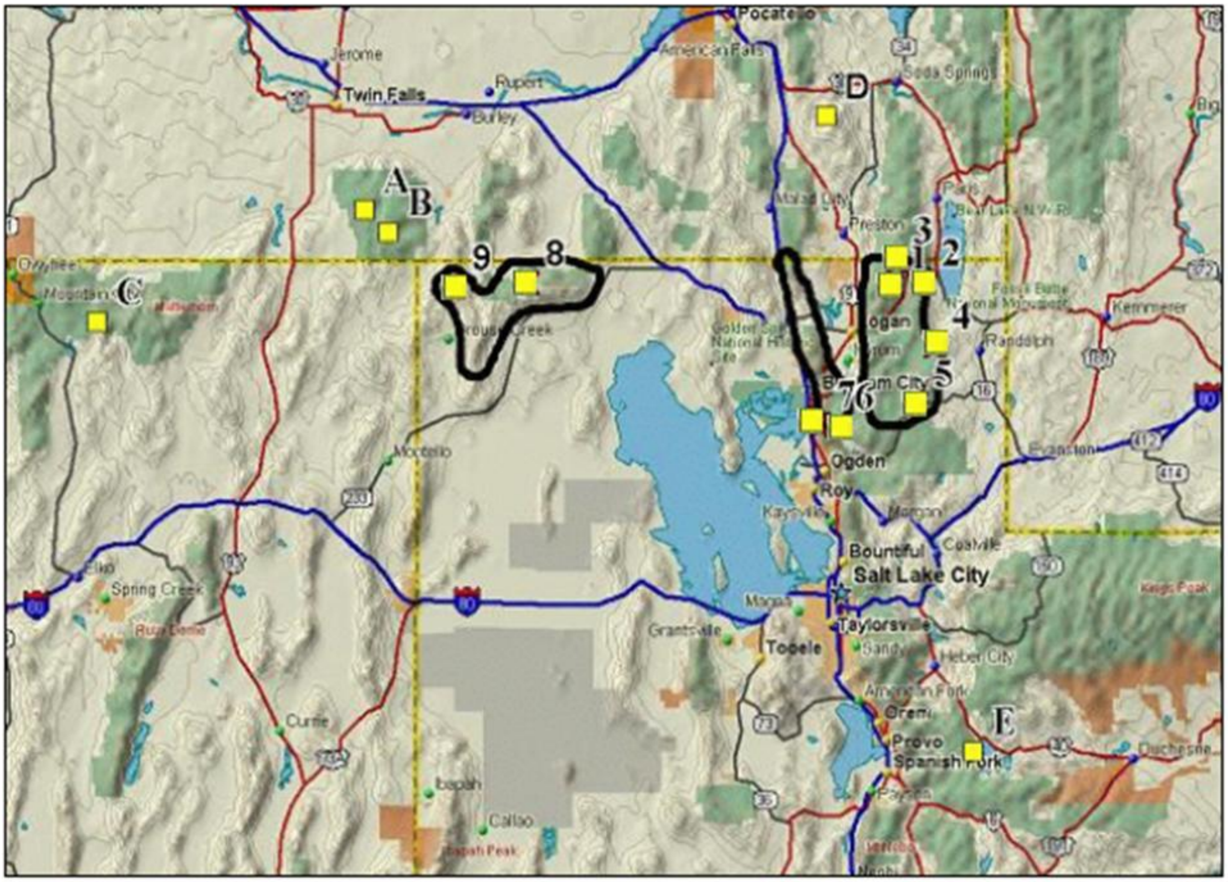


Figure 5.6 **Target and control sites used in eastern Box Elder/Cache County snowpack evaluation, with site data shown in Table 4-2. The target areas are outlined in black. The target sites are numbered; the control sites have letter ID's.**

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:

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

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:

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

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:

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

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 0.97, 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

$$Y_C = 1.78 + 0.78(X_1) + 0.67(X_2) \tag{7b}$$

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:

$$Y_C = 2.09 + 0.36(X_1) + 0.43(X_2) - 0.18(X_3) + 0.13(X_4) + 0.33(X_5) \tag{8a}$$

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 0.94 as compared to 0.91 from the linear regression equation.

$$Y_C = 2.78 + 0.72(X_1) + 0.25(X_2) \tag{8b}$$

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, 2020 snow water content averaged 16.14 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 24.75 inches. The measured average target area water content was 24.34 inches, which yields an observed/predicted ratio of 0.98 for the eastern Box Elder/Cache County portion of the target. The average increase for the 31 seeded seasons (excluding 2017 as previously noted) is about 7%. The corresponding average estimated increase in snow water content (which could be attributed to seeding) is approximately 1.5 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. As a consequence, snow water content measurements on April 1st 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).

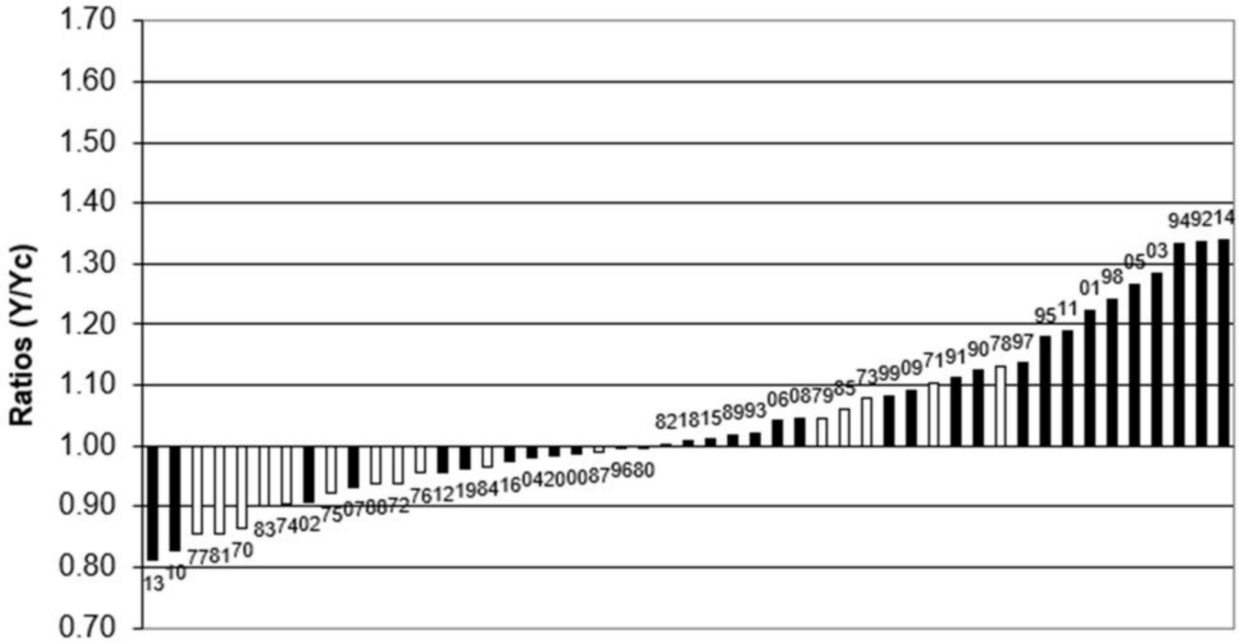


Figure 5.7 Observed/predicted ratios for 1970-2020 April 1st snow water content, using the linear regression technique, Eastern Box Elder/Cache Counties. White bars = historical (unseeded) seasons; black bars = seeded seasons

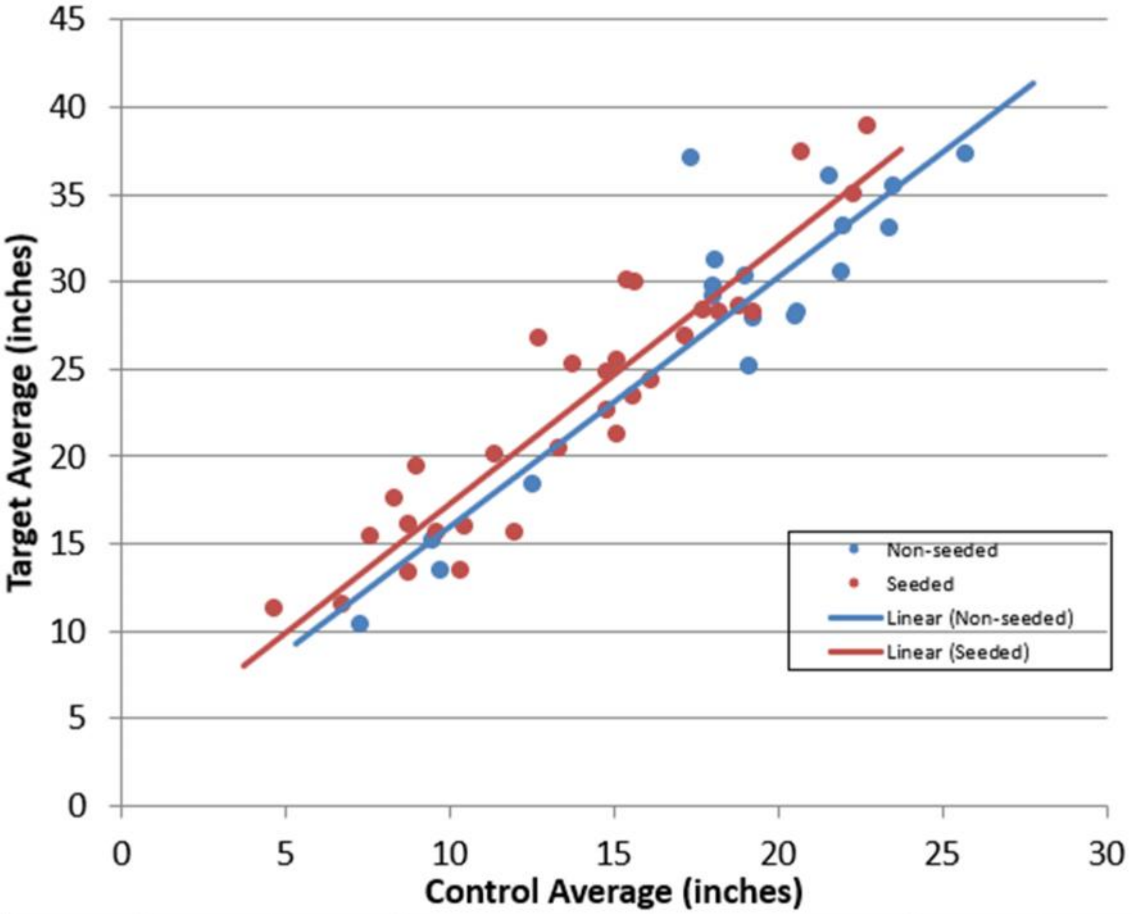


Figure 5.8 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for eastern Box Elder and Cache County snowpack linear regression.

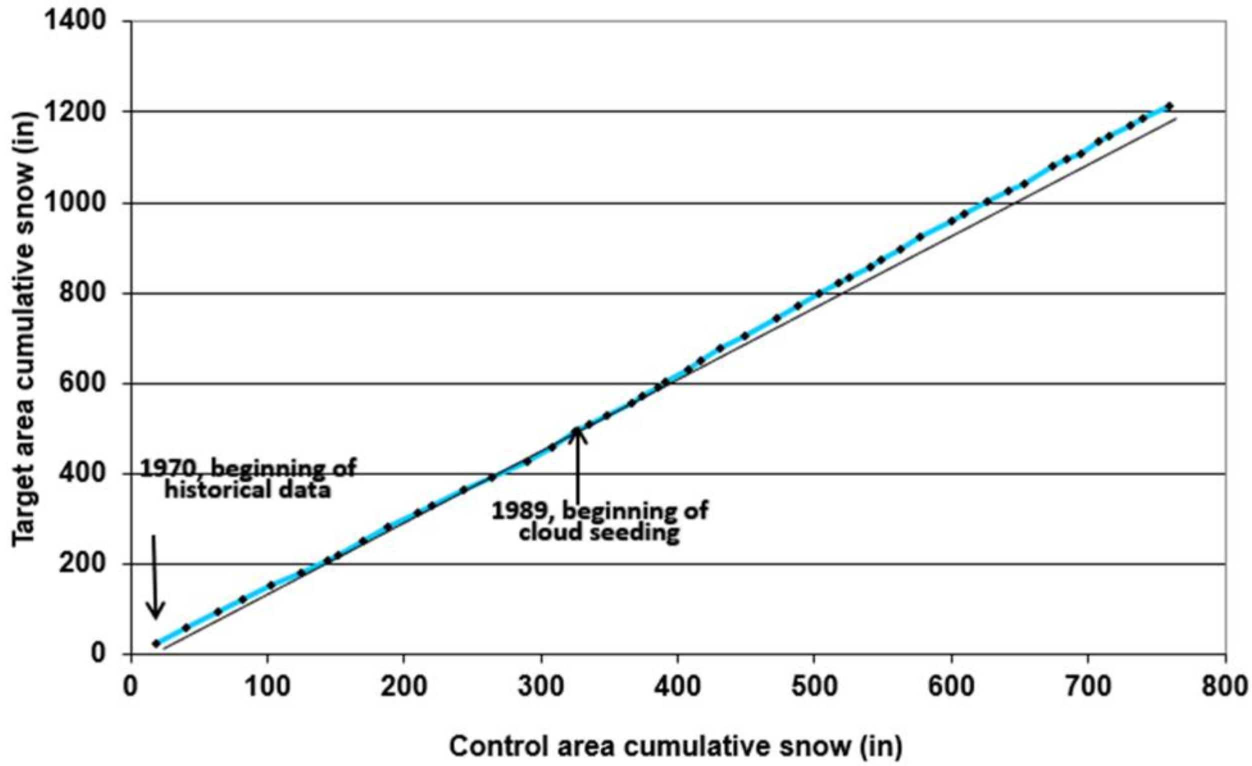


Figure 5.9 Double mass plot showing cumulative April 1 snow water content amounts for eastern Box Elder and Cache County target and control areas, water years 1970-2020.

In the northwestern Box Elder County portion of the target, the April 1, 2020 observed water content was 18.64 inches, with a predicted value of 17.45 inches. This yields an observed/predicted ratio of 1.07 for the northwestern Box Elder County portion of the target for this season. The average increase for the 27 seeded seasons (through 2020) is 13%, and the average estimated increase in snow water content is close to 2.0 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.

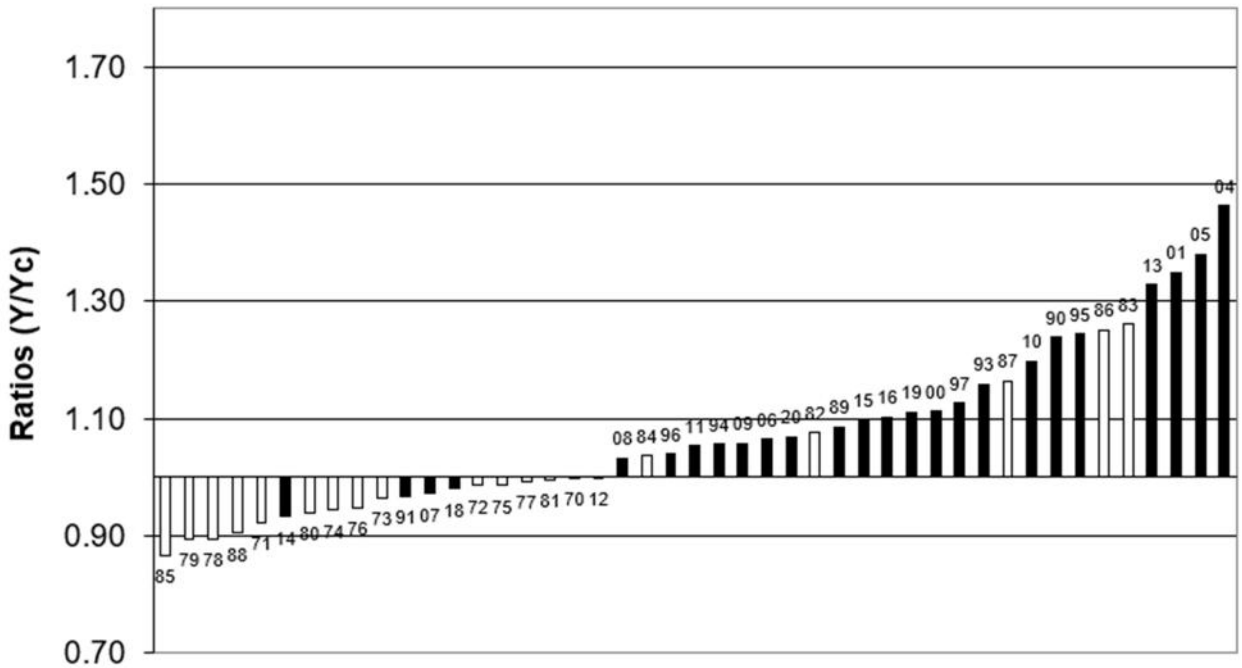


Figure 5.10 Observed/predicted ratios for 1970-2020 April 1st snow water content, using the linear regression technique, <u>Northwest Box Elder County</u>. White bars are historical (unseeded) seasons; black bars = seeded seasons; 1998, 1999, 2002, and 2003, are not shown because of no seeding in those years. 2017 was also excluded.

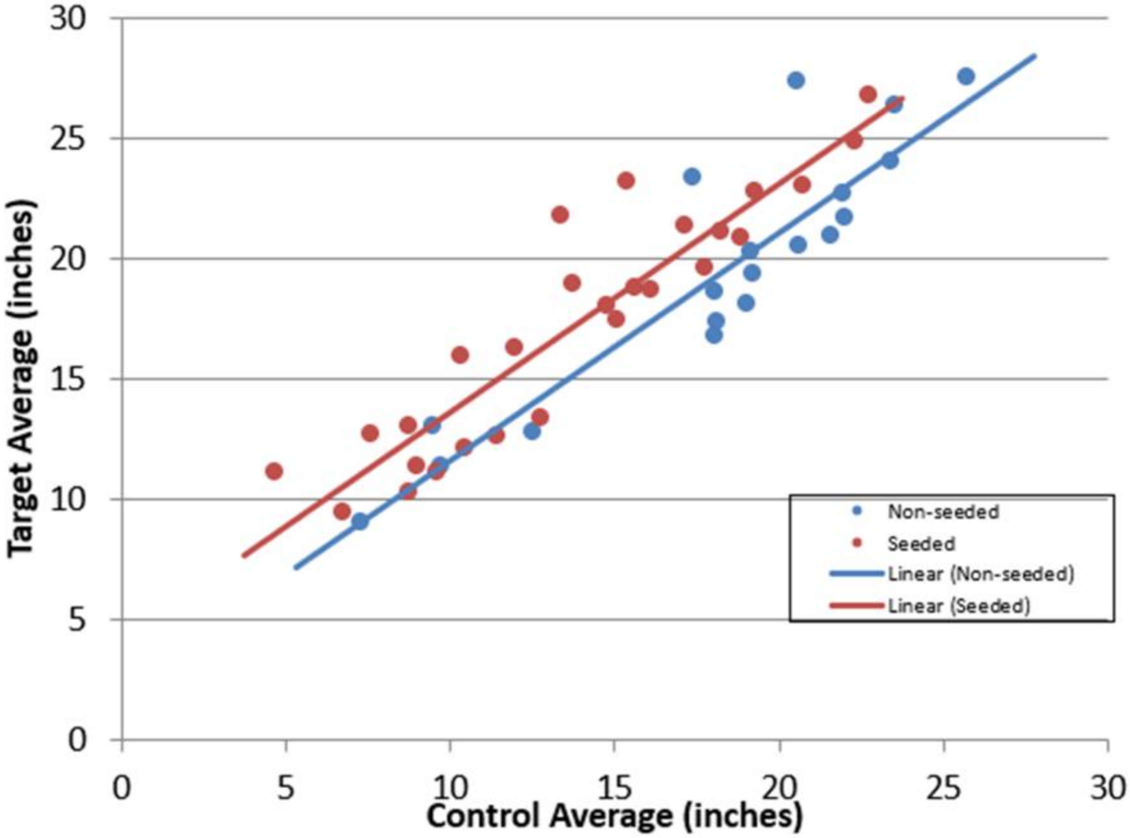


Figure 5.11 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for Northwest Box Elder County snowpack linear regression

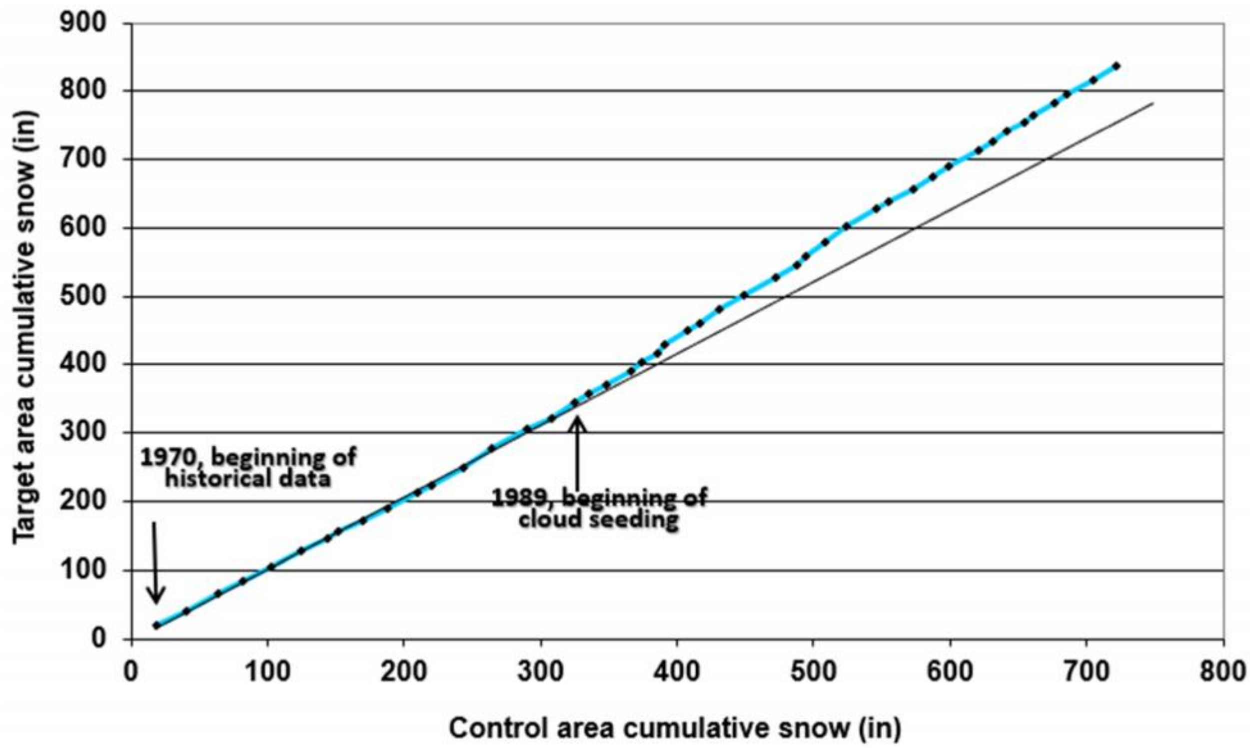


Figure 5.12 Double mass plot showing cumulative April 1 snow water content amounts for Northwest Box Elder County target and control areas for water years 1970-2020 (plot excludes the water years 1998, 1999, 2002, and 2003, when no seeding was conducted, as well as water year 2017).

5.3.2.5 Results of Multiple Linear Regression Snowpack Evaluation

The multiple regression evaluation resulted in ratios of 1.10 and 0.97 this season for the Eastern Box Elder/Cache County area and the Northwestern Box Elder County area, respectively. The long-term indications (through 2020) include a 12% 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 31 seasons of seeding. These results are similar to the linear regression equations results. For northwestern Box Elder County, the long-term analysis shows a 9% increase (about 1.5 inches of additional snow water) based on the multiple linear equation for 27 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 variable, as is frequently the case. Table 5-3 (repeated in Section 6.0 of the report) summarizes the individual season and cumulative results of the various target/control evaluations conducted for this program.

The long-term results for 31 seeded seasons in the Eastern Box Elder/Cache County portion of the target indicate 7-12% increases in April 1 snowpack (an average of 1.5-2.5 inches of excess water) and a 6-7% increase in December through March precipitation (over 1.0" of additional water). These cumulative results likely constitute reasonable estimates of the true seeding effects for this program. 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 the actual effects of the seeding from one season to another.

Table 5-3
Comparison of Results of Linear and Multiple Linear Analyses, 2019-2020 and all Seeded Seasons.

Area	Ratio Observed/Predicted		Excess Water (inches)	
	Linear	Multiple Linear	Linear	Multiple Linear
Cache/E. Box Elder Dec-Mar Precip.	2020: 0.91 **31 yrs: 1.06**	2020: 0.95 **31 yrs: 1.07**	2020: -1.8 **31 yrs: +1.0**	2020: -0.9 **31 yrs: +1.2**
Cache/E. Box Elder April 1 Snowpack	2020: 0.98 **31 yrs: 1.07**	2020: 1.10 **31 yrs: 1.12**	2020: -0.4 **31 yrs: +1.5**	2020: 2.3 **31 yrs: +2.5**
NW Box Elder April 1 Snowpack	2020: 1.07 **27 yrs: 1.13**	2020: 0.97 **27 yrs: 1.09**	2020: +1.2 **27 yrs: +2.0**	2020: -0.6 **27 yrs: +1.5**

Snowpack evaluations for the Northwestern Box Elder County portion of the target area this season produced single season observed/predicted ratios of 1.07 (linear regression) and 0.97 (multiple linear). The long-term results indicate average increases for the 27 seeded seasons of +13% (linear) and +9% (multiple linear), which is equivalent to about 1.5 – 2.0 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.

6.0 SUMMARY AND RECOMMENDATIONS

Operational cloud seeding, designed to enhance wintertime precipitation and snowpack in Utah's mountains, offers a cost-effective method of increasing water supplies. A cloud seeding program was again conducted during the 2019-2020 winter season for the mountainous areas of Box Elder and Cache Counties in northern Utah. The cloud seeding program uses an array of ground-based cloud nuclei generators (currently 31 sites in all) and a fast-acting seeding formulation. The project was operational from December 1, 2019 through March 31, 2020 for portions of Box Elder and Cache Counties. During the season, there were 18 seeding operations conducted on portions of 28 days. Three storms were seeded in December, six in January, three in February (including one split between February and March), and six additional storms were seeded in March. A cumulative 1,797.5 hours of operations were conducted from all the generator sites during the season.

Precipitation was near normal in northern Utah during the 2019-2020 winter season. Snowpack in the Bear River Basin on April 1, 2020 averaged 110% of normal (median), with about 94% of the normal (mean) water year to precipitation to date.

6.1 Evaluations of Seeding Effectiveness

Linear regression equations based on historical relationships between "target" and "control" area average December - March precipitation, as well as April 1 snowpack, have been developed and used to estimate seeding effects during the seeded seasons through the history of the project. Target/control linear regression evaluations of the 2019-2020 winter season, for the Eastern Box Elder/Cache County portions of the target, show observed-to-predicted ratios of 0.91 and 0.98 for precipitation and snowpack, respectively. **The long term (all seeded seasons) average for December - March precipitation shows an average 6% increase for eastern Box Elder/Cache County portion of the project area, with a 7% average increase in April 1st snow water content indicated for the 31-season seeded period through 2020. In analyses of this type it is typical to see a lower indicated percentage effect in the snow water content evaluation, in the long-term results, since seeding is not conducted during the entire snowpack accumulation period. The long-term results are much more significant and likely more representative of the true seeding effect than any single season results.**

For Northwest Box Elder County, the 2019-2020 linear snowpack evaluation resulted in an observed/predicted ratio of 1.07. **The average increase in April 1st snow water content in northwest Box Elder County is 13% for the 27 seasons of seeding included in this analysis.**

Table 6-1 provides a comparison of results obtained using the two (precipitation and snowpack water content) techniques. There are no data (measurements) in the northwest Box Elder County target area with a long enough history to evaluate the seeding effects based upon precipitation gage measurements.

Multiple linear regression analysis was also performed for the program. This evaluation consisted of the development and application of multiple linear regression equations for both precipitation and snowpack. The multiple linear regression technique is also used in evaluating some of the other NAWC winter programs being conducted in Utah. This technique is quite similar to the linear regression, using the same target and control stations. The difference is that instead of averaging all of the control site precipitation or snow water content observations, each control site (or alternatively, groups of control sites) is compared to the target area average. This technique produces higher correlations than obtained using the linear regression method. Equations with higher correlations may provide more accurate estimates of what the precipitation in the target areas would be in the absence of seeding, if (importantly) an adequate base period for development of the equation is available.

The single-season results obtained using the multiple linear regression technique are somewhat different than those obtained using the simple linear regression technique. Table 6-1 provides a comparison of results obtained using the two techniques, and shows that the long-term results obtained using the two evaluation techniques are similar, providing somewhat greater confidence in the indicated effects. Bottom-line indications based on these various regression analyses are that the seeding program has, on average, yielded seasonal precipitation/snowpack increases in the 6-13% range for the target areas.

NAWC produced various plots for the precipitation and snowpack analyses (described and shown in Section 5.4), which provide visual indications of long-term seeding effects. These plots highlight the change in the target/control relationship between the historical regression period and the seeded period.

The value of the cloud seeding program was clearly demonstrated in an independent study performed by the Utah Division of Water Resources entitled "Utah Cloud Seeding Program, Increased Runoff/Cost Analyses" (Stauffer and Williams, 2000). The study report used estimates of increases in April 1st water content from an earlier NAWC annual project report (similar to this one), with verification of those numbers by the Division, to estimate increases in streamflow due to cloud seeding. The report was updated by the Division in 2012 (Hasenyager, et al, 2012). The results of this report for the various seeding target areas in Utah are summarized in Table 6-2.

Table 6-1
Comparison of Results of Linear and Multiple Linear Analyses, 2019-2020 and all Seeded Seasons.

Area	Ratio Observed/Predicted		Excess Water inches	
	Linear	Multiple Linear	Linear	Multiple Linear
Cache/E. Box Elder Dec-Mar Precip.	2020: 0.91 **31 yrs: 1.06**	2020: 0.95 **31 yrs: 1.07**	2020: -1.8 **31 yrs: +1.0**	2020: -0.9 **31 yrs: +1.2**
Cache/E. Box Elder April 1 Snowpack	2020: 0.98 **31 yrs: 1.07**	2020: 1.10 **31 yrs: 1.12**	2020: -0.4 **31 yrs: +1.5**	2020: 2.3 **31 yrs: +2.5**
NW Box Elder April 1 Snowpack	2020: 1.07 **27 yrs: 1.13**	2020: 0.97 **27 yrs: 1.09**	2020: +1.2 **27 yrs: +2.0**	2020: -0.6 **27 yrs: +1.5**

Table 6-2 Increased Runoff and Cost for the Utah Cloud Seeding Projects

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

The 2012 DWR report estimated an average annual increase in runoff due to cloud seeding in Utah of 181,700 acre-feet, which is an increase of 5.7 percent. The resulting state-wide average cost per acre-foot for the additional water was $2.27 based upon the 2009-2010 total project costs, while the Northern Utah project cost per acre foot was estimated at approximately $1.55. Assuming an estimated average value of the enhanced runoff in the Northern Utah project watersheds at $10-15 per acre foot, the benefit/cost ratio for the overall project would be of the order of 6.5/1 to 9.7/1.

6.2 Recommendations

It is recommended that the winter seeding programs over the mountainous portions of northern Utah be continued. Routine application of weather modification technology year after year can help stabilize and bolster both surface and underground water supplies. Commitments to conduct a program each winter provide stability and acceptance by funding agencies and the general public. The current program is designed so that it can be temporarily suspended or terminated during a given winter season, if snowpack levels accumulate to the point where additional water will not be beneficial.

There are several reasons to conduct the program on an ongoing basis: 1) it is very difficult to predict when a dry winter will occur, 2) a season could start out wet but turn dry, and the seeding opportunities in the wet period would be missed if the start of seeding was delayed, 3) drier seasons, by definition, will have fewer seeding opportunities, and thus offer less frequent potential for increasing water supplies, and 4) seeding in normal and above normal water years will provide additional water supplies (surface and underground) for use during dry periods.

In summary, weather modification during the winter season is a viable and valuable, cost-effective alternative for enhancing water supplies in Utah. Specifically, the winter cloud seeding project described in this report is achieving its stated goal of augmenting the winter snowpack over the mountains and producing more usable water via the spring and summer runoff.

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APPENDIX A

CLOUD SEEDING SUSPENSION CRITERIA

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

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

1. Excess snowpack accumulation

2. Rain-induced winter flooding

3. Severe weather

1. Excess Snowpack Accumulation

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

Project & Basin	Critical Streamflow Volume (Acft) & USGS Streamgage	SNOTEL Station	SWE Value Corresponding to the Critical Flow								Ranking of SNOTEL Stations
			Jan 1 (in.)	Jan 1 (%)	Feb 1 (in.)	Feb 1 (in %)	March 1 (in.)	March 1 (in %)	April 1 (in.)	April 1 (in %)	
1. Northern Utah	185,208	Franklin Basin, Idaho	19.50	190.84	27.14	165.31	34.35	154.71	41.56	153.60	1
Logan at Logan	USGS 10109000	Tony Grove	28.73	205.94	39.44	175.56	48.06	160.38	56.34	156.56	2
		Bug Lake	17.08	218.82	21.91	180.34	26.72	165.25	31.65	162.70	3
		Average	**21.80**	**205.20**	**29.50**	**173.70**	**36.40**	**160.10**	**43.20**	**157.60**	
Weber near Oakley	176,179	Chalk Creek #1	10.09	173.13	14.73	153.66	28.77	149.85	34.15	143.41	1
	USGS 10128500	Trial Lake	20.15	207.44	26.33	180.55	33.55	173.27	38.54	162.28	2
		Smith Morehouse	10.06	186.54	13.69	157.60	17.36	146.52	21.17	160.26	3
		Hayden Fork	12.19	194.16	16.69	172.11	20.71	158.56	21.79	164.64	4
		Average	**13.10**	**190.30**	**17.90**	**166.00**	**25.10**	**157.10**	**28.90**	**157.70**	
Dunn Creek near the Park Valley	5,733	George Creek	17.84	187.75	18.32	143.81	28.93	163.43	34.61	153.77	1
	USGS 10172952	Howell Canyon, Idaho	28.71	279.96	38	223.24	44.59	205.98	50.46	191.65	2
		Average	**23.30**	**233.90**	**28.20**	**183.60**	**36.80**	**184.70**	**42.60**	**172.70**	
2. Western & High Uintah	166,861	Lily Lake	11.38	202.70	16.40	194.06	17.69	147.37	28.93	139.19	1
Bear River near Utah - Wyoming state line	USGS 10011500	Trial Lake	20.07	206.54	26.56	182.26	33.68	173.94	38.49	162.05	2
		Hayden Fork	12.41	197.65	17.06	175.83	21.03	160.98	20.90	146.02	3
		Average	**14.60**	**202.30**	**20.00**	**184.10**	**24.10**	**160.80**	**29.40**	**149.10**	
Duchesne near Tabiona	140,976	Strawberry Divide	6.92	239.23	10.87	199.25	26.77	178.78	29.75	179.05	1
	USGS 09277500	Daniels-strawberry	16.07	248.12	21.59	202.44	27.82	190.54	29.89	192.75	2
		Smith Morehouse	10.61	196.64	14.95	172.41	18.82	158.83	22.22	168.26	3
		Rock Creek	8.76	230.02	12.31	219.65	15.88	205.68	16.41	209.06	4
		Average	**10.60**	**228.50**	**14.90**	**198.50**	**22.30**	**183.50**	**24.60**	**187.30**	
Provo near woodland	183,845	Trial Lake	22.98	236.53	27.78	190.63	35.23	181.59	31.44	132.39	1
	USGS 09277500	Beaver Divide	10.29	210.39	14.11	179.49	17.45	170.83	20.18	200.3	2
		Average	**16.70**	**223.50**	**20.90**	**185.10**	**26.30**	**176.20**	**25.80**	**166.40**	
3. Central & Southern	120,473	Castle Valley	12.23	244.05	16.96	203.04	22.22	187.68	26.30	180.00	1
Sevier near Hatch	USGS 10174500	Harris Flat	8.71	298.76	15.25	273.59	24.16	222.99	21.15	209.77	2
		Farnsworth Lake	17.25	218.10	20.96	185.95	27.05	182.24	32.93	167.03	3
		Average	**12.80**	**253.70**	**17.70**	**220.90**	**24.50**	**197.70**	**26.80**	**185.60**	
Coal Creek near Cedar City	38,533	Midway Valley	20.89	215.65	29.12	194.04	35.89	176.99	42.29	167.97	1
	USGS 10242000	Webster Flat	13.57	232.46	18.70	197.95	24.30	184.64	24.93	181.12	2
		Average	**17.20**	**224.10**	**23.90**	**196.00**	**30.10**	**180.90**	**33.60**	**174.60**	
South Willow near Grantsville	5,426	Rocky Basin-settlemnt	19.09	205.33	23.75	174.14	32.11	171.39	40.01	167.51	1
	USGS 10172800	Mining Fork	16.31	243.66	20.74	177.04	27.81	171.79	32.19	168.74	2
		Average	**17.70**	**224.50**	**22.30**	**175.60**	**30.00**	**171.60**	**36.10**	**168.10**	
Virgin River at Virgin	151,286	Kolob	23.11	229.25	29.08	220.78	36.51	197.43	43.71	196.21	1
	USGS 09406000	Harris Flat	9.71	377.00	15.69	304.18	21.46	300.00	20.11	370.00	2
		Midway Valley	24.76	256.17	34.56	238.40	41.44	209.68	51.05	211.06	3
		Long Flat	9.38	265.88	13.54	286.16	19.20	286.18	18.91	187.00	4
		Average	**16.70**	**282.10**	**23.20**	**262.40**	**29.70**	**248.40**	**33.40**	**241.10**	
Santa Clare above Baker Reservoir	11,620	Gardner Peak	13.00	293.90	16.82	172.15	21.70	167.36	24.45	163.95	1
	USGS 09409100	**Average**	**13.00**	**293.90**	**16.80**	**172.10**	**21.70**	**167.40**	**24.50**	**164.00**	
		Utah State Average (%)		**230**		**197**		**183**		**178**	
		Standard Deviation		**42**		**38**		**35**		**42**	
		Upper 95%		**248**		**213**		**199**		**196**	
		Lower 95%		**212**		**180**		**168**		**160**	

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

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

2. Rain-induced Winter Floods

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

3. Severe Weather

During periods of hazardous weather associated with both winter orographic and convective precipitation systems it is sometimes necessary or advisable for the National Weather Service (NWS) to issue special weather bulletins advising the public of the weather phenomena and the attendant hazards. Each phenomenon is described in terms of criteria used by the NWS in issuing special weather bulletins. Those 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, 2019-2020

Table B-1
Generator Hours – Northern Utah, 2019 – 2020, Storms 1-10

Stor	1	2	3	4	5	6	7	8	9	10
Dates	**Dec 8-9**	**Dec 12-**	**Dec 14**	**Jan 1-2**	**Jan 8**	**Jan 12-13**	**Jan 14**	**Jan 16-**	**Jan 28-**	**Feb 2-3**
SITE										
1-1										
1-3				21.5					5	
1-4										
1-5										
1-6										
1-7		12.75		17			3			
1-8		13		19			4		5	
1-9										
1-10	11.5	6		1			3.75		11	
1-11				17.5		11.75			10	
1-12	14			17.5		11			10	
1-13		13.5	7.5	18.75	2	11		9	11.5	8.25
1-14		13	9	19.25		11				
1-15		13	7.5	18.5	2.5	11	5.25	5	10.5	10.5
1-16			8				3.5		10	
1-17										
2-1		13.25	7.75	22		11	4		10.5	
2-2			8.5	22.5	3.25	11	4		10	
2-3		14.25	0	24.5	3.5		4.5	13.75		
2-4	14.75	12.75	9	24		11	4.25	12	11	10
2-5	14.5	13	8	24		11	5	14.75	11	10.25
2-7		13.75	0	22.25					10	
2-8	14.25	14	7.75	24.5	3.5	6	5.25	13.5	11	
2-9		13.75	0			11	5.5	13.5		

2-10		8	0	17.5		11	5.5	5		
2-11			7.5	24.25	3.5		5.5			
2-12								9.5		
3-3										
3-6										
3-7										
3-8	15.25	12.5	9				5.25			
Storm	**84.25**	**186.5**	**89.5**	**355.5**	**18.25**	**127.75**	**68.25**	**96**	**136.5**	**39**

Table B-2
Generator Hours – Northern Utah, 2019 – 2020, Storms 11-18

Storm	11	12	13	14	15	16	17	18	Site Totals
Dates	**Feb 16-17**	**Feb 29 –**	**Mar 14-15**	**Mar 18**	**Mar 21**	**Mar 24-25**	**Mar 30**	**Mar 31**	
SITE									
1-1									0
1-3		10							36.5
1-4									0
1-5						5			5
1-6						5			5
1-7									32.75
1-8						7.25			48.25
1-9			22						22
1-10							2.5		35.75
1-11						18.25			57.5
1-12									52.5
1-13	15					23.25	2.75		122.5
1-14	15					18		8.5	93.75
1-15	15			2.75		23.5		9	134
1-16	14					23.25		2	60.75
1-17									0
2-1					3	18.25			89.75
2-2						20.5	2.5		82.25
2-3						23	2.5		86
2-4	14					18.5	2.5		143.75
2-5				3	3	21			138.5
2-7						23.75		8.5	78.25
2-8	14.75								114.5
2-9						22		8	73.75

2-10				6		16.5			69.5
2-11						25.25		8.5	74.5
2-12	8					25.5		8.5	51.5
3-3				4					4
3-6						6.5			6.5
3-7						7.75		8.5	16.25
3-8	14			3.25	3				62.25
Storm	**109.75**	**10**	**22**	**19**	**9**	**352**	**12.75**	**61.5**	

APPENDIX C

PRECIPITATION AND SNOWPACK EVALUATION DATA/RESULTS

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

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:					
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
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

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
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
Mean	13.87	18.94	17.91	**1.06**	**1.03**

* 2017 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

	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
Mean	19.85	12.57	14.88	8.15	18.94	17.75	**1.07**	**1.19**

* 2017 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

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

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
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
Mean	13.80	22.90	21.40	**1.07**	**1.50**

* 2017 not included in mean values

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.911075
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

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

YEAR	Magic Mtn Pil	Badger Gulch Sc	Big Bend Pil	Sedgewick Pk Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
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
Mean	17.52	11.50	6.20	19.05	14.75	22.90	20.41	**1.12**	**2.49**

* 2017 not included in mean values

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
Mean	13.84	17.23	15.27	**1.13**	**1.96**

* No seeding in these seasons, not included in mean
** 2017 not included in mean values due to suspensions

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
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 Pil	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

YEAR	Magic Mtn Pil	Badger Gulch SC	Sedgewick Pk Pil	Big Bend Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
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
Mean	17.5	11.5	19.1	6.1	15.0	17.2	15.8	**1.09**	**1.48**

* No seeding in these seasons, not included in mean
** 2017 not included in mean values due to suspensions

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.

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

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

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

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