SUMMARY AND EVALUATION OF 2018-2019 WINTER CLOUD SEEDING OPERATIONS IN BOX ELDER and CACHE COUNTIES, UTAH

Prepared for

Bear River Water Conservancy District
Box Elder County
Cache County
State of Utah, Division of Water Resources

by

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Mark E. Solak

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Report No. WM 19-3
Project No. 18-421

June 2019

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SUMMARY AND EVALUATION OF
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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 2018-2019 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 intended target area of the program consists of the mountainous portions of Cache County and Box Elder County 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.

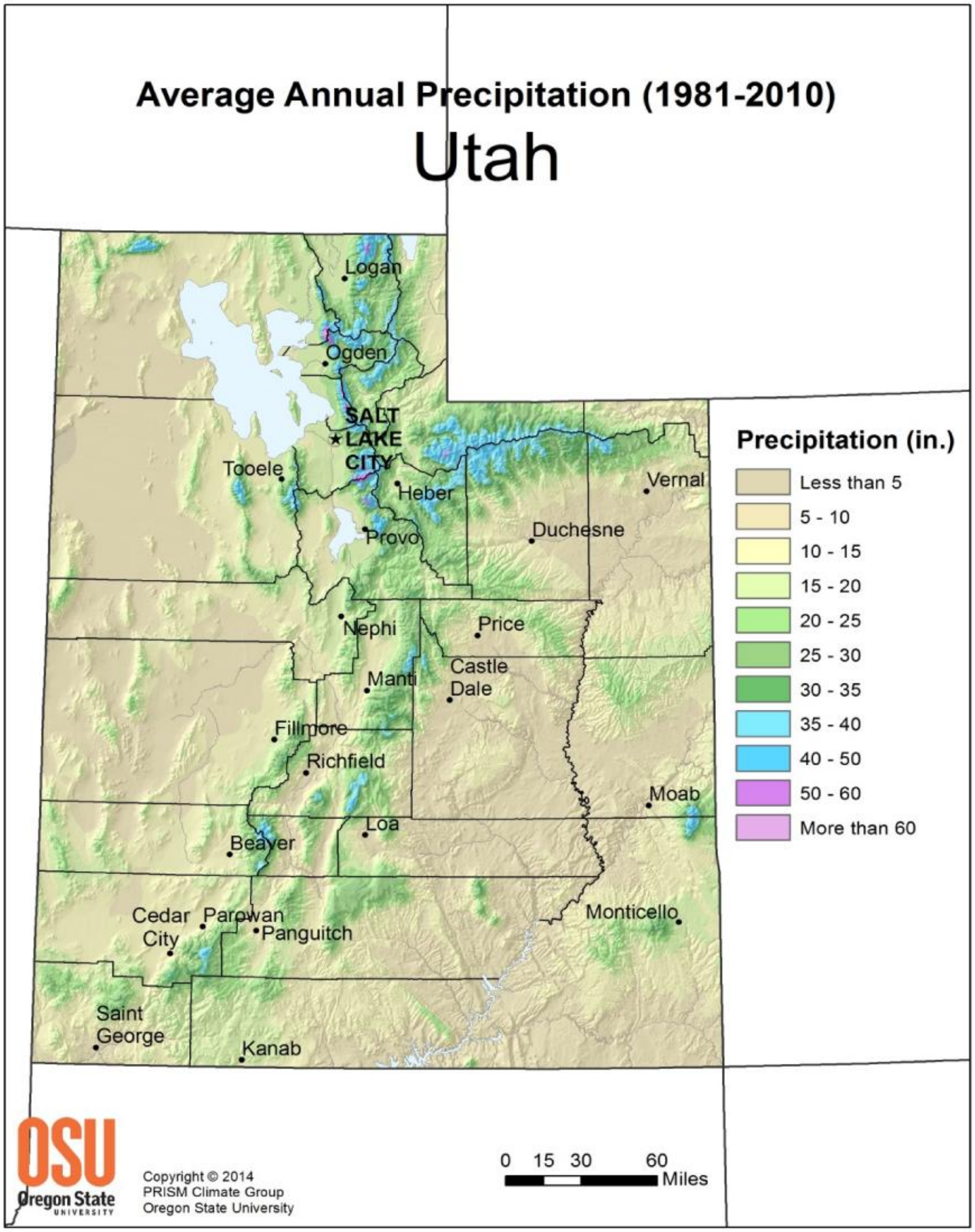


Figure 1.1 Average annual precipitation in Utah.

Cloud seeding in the state is regulated by the Utah Department of Natural Resources. 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 2018-2019 winter season. Section 2.0 contains a brief background on cloud seeding technology and the design of the seeding program. Section 3.0 discusses the types of real-time and forecast meteorological data that are used for conduct of the seeding programs. Section 4.0 summarizes the seeding operations conducted during this past season. Section 5.0 details statistical evaluations of the effects of the cloud seeding program. A summary and recommendations for future seasons are given in Section 6.0.

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

Project 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 Table 2-1. 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 2018, 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.

Table 2-1

NAWC Winter Cloud Seeding Criteria

1) CLOUD BASES ARE BELOW THE MOUNTAIN BARRIER CREST.

2) LOW-LEVEL WIND DIRECTIONS AND SPEEDS THAT WOULD FAVOR THE MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THEIR RELEASE POINTS INTO THE INTENDED TARGET AREA.

3) NO LOW LEVEL ATMOSPHERIC INVERSIONS OR STABLE LAYERS THAT WOULD RESTRICT THE VERTICAL MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THE SURFACE TO AT LEAST THE -5°C (23°F) LEVEL OR COLDER.

4) TEMPERATURE AT MOUNTAIN BARRIER CREST HEIGHT IS -5°C (23°F) OR COLDER.

5) TEMPERATURE AT THE 700 MB LEVEL (APPROXIMATELY 10,000 FEET) IS WARMER THAN -15°C (5°F).

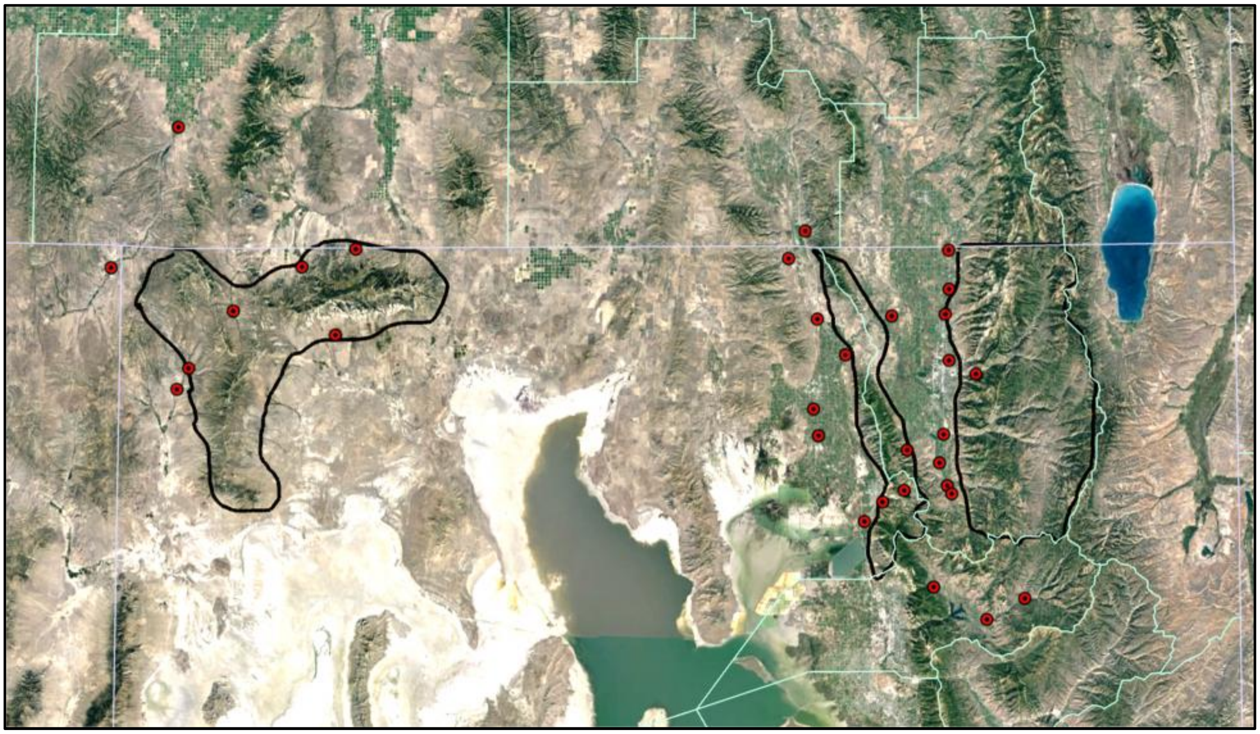


Figure 2.1 CNG sites and seeding target areas for the 2018-2019 Northern Utah Program; site 1-1 near Oakley, Idaho is farther north than it appears on this map.

2.3.1 Ground-Based Manual Silver Iodide Generators

The cloud seeding equipment consists of ground-based cloud nucleating 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 CNG's 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 $\leq$ -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.

It is necessary that the AgI 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 AgI 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.

2.3.2 Ground Generator Locations

There were 31 available seeding generators located in Cache County, Box Elder County, and Weber County for seeding the target areas. One CNG was located in southern Idaho, for seeding northwestern Box Elder County. Figure 2.1 shows the CNG site locations and seeding target for the project. These are essentially the same site locations that were utilized during the previous seasons, with the addition of a site near the Idaho/Nevada border to seed northwestern Box Elder County. A couple of the previous, lesser-used sites in that area were also replaced with other sites. Pertinent site information is listed in Table 2-2.

The process of choosing sites for the generators involves studying topographical maps and identifying general areas most suitable, taking into account 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 Pacific Ocean from the southwest, west, or northwest. They often consist of a frontal system and/or an upper trough, with south or southwesterly winds (in meteorology, winds 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 2-2

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'

2.3.3 Suspension Criteria

NAWC conducts all its projects within guidelines adopted to ensure public safety. Accordingly, NAWC has, in coordination with the Utah DWR, developed policies, criteria and procedures for the suspension or curtailment of cloud seeding operations within the project area and those criteria have been incorporated into its operational routine. Appendix A contains the suspension criteria. For the 2018-2019 season, snowpack percentages were somewhat above the seasonal average but there were no suspensions for the Northern Utah program.

2.4 Operations Center

NAWC maintains a fully equipped project operations center at its Sandy, Utah headquarters. Information is continuously acquired and updated from the National Weather Service (NWS) as well as from a wide variety of other sources, including subscriber services. This array of information is acquired online and includes weather satellite and radar data, data from computer forecast models, real-time surface observations, various weather cameras, as well as other types of information. This helps NAWC’s meteorologists to determine when conditions are appropriate for cloud seeding. Each of NAWC’s meteorologists also has a fully capable computer system with internet access at home, to allow continued monitoring and conduct of seeding operations outside regular business hours. Section 3.0 of this report details several types of current and forecast weather information used in the conduct of operations.

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, NEXRAD radar information, and weather cameras. This information helps NAWC meteorologists to determine when conditions are appropriate for cloud seeding. Each of NAWC's meteorologists also has a fully capable computer system with internet access at home, to allow continued monitoring and conduct of seeding operations outside regular business hours. Figures 3.1 – 3.3 show examples of some of the available weather information that was used in this decision-making process during the 2018-2019 winter season. Figure 3.4 provides predictions of ground-based seeding plume dispersion for a discrete storm period in central and southern Utah using the National Oceanic and Atmospheric Administration's HYSPLIT model (Appendix B). This model helps to estimate the horizontal and vertical spread of a plume from potential ground-based seeding sites in real-time, based on wind fields contained in the weather forecast models.

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

A more recent product to which NAWC obtained access provides the ability to display special High-Resolution Rapid Refresh (HRRR) model meteorological data in support of operations. The software used by NAWC was developed by Idaho Power Company in support of their cloud seeding operations primarily by providing analyses and forecasts of supercooled liquid water, temperature, moisture, and other parameters relevant to operations. The HRRR model does not forecast seeding effects, or the dispersion of seeding material such as the

HYSPLIT model does, but it contains important atmospheric parameters in much finer time and space resolution than other (e.g. global) weather forecast models. An example of HRRR products is shown in Figure 3.6.

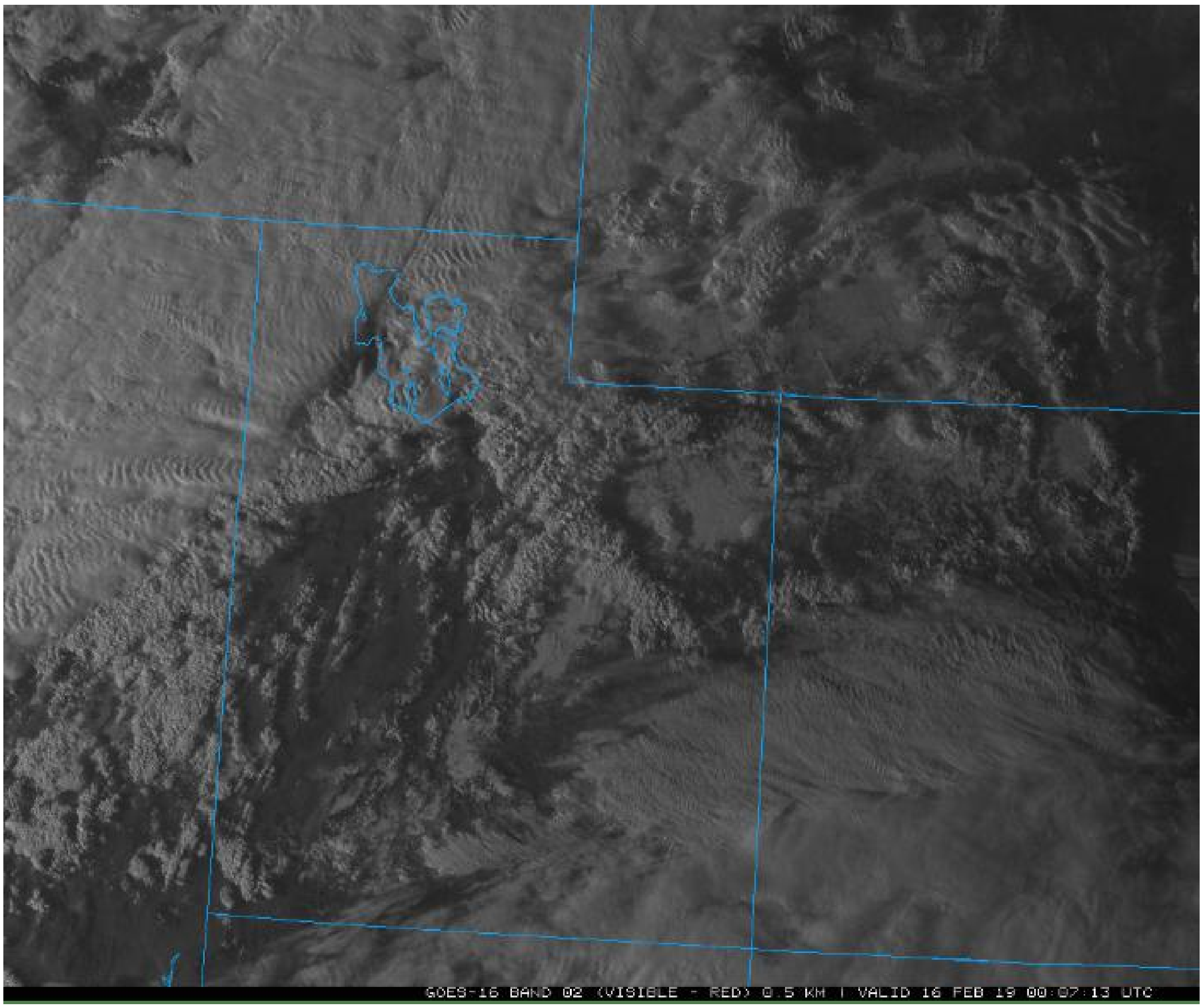


Figure 3.1 Visible spectrum satellite image on February 16 as a cold frontal boundary moved across northern Utah

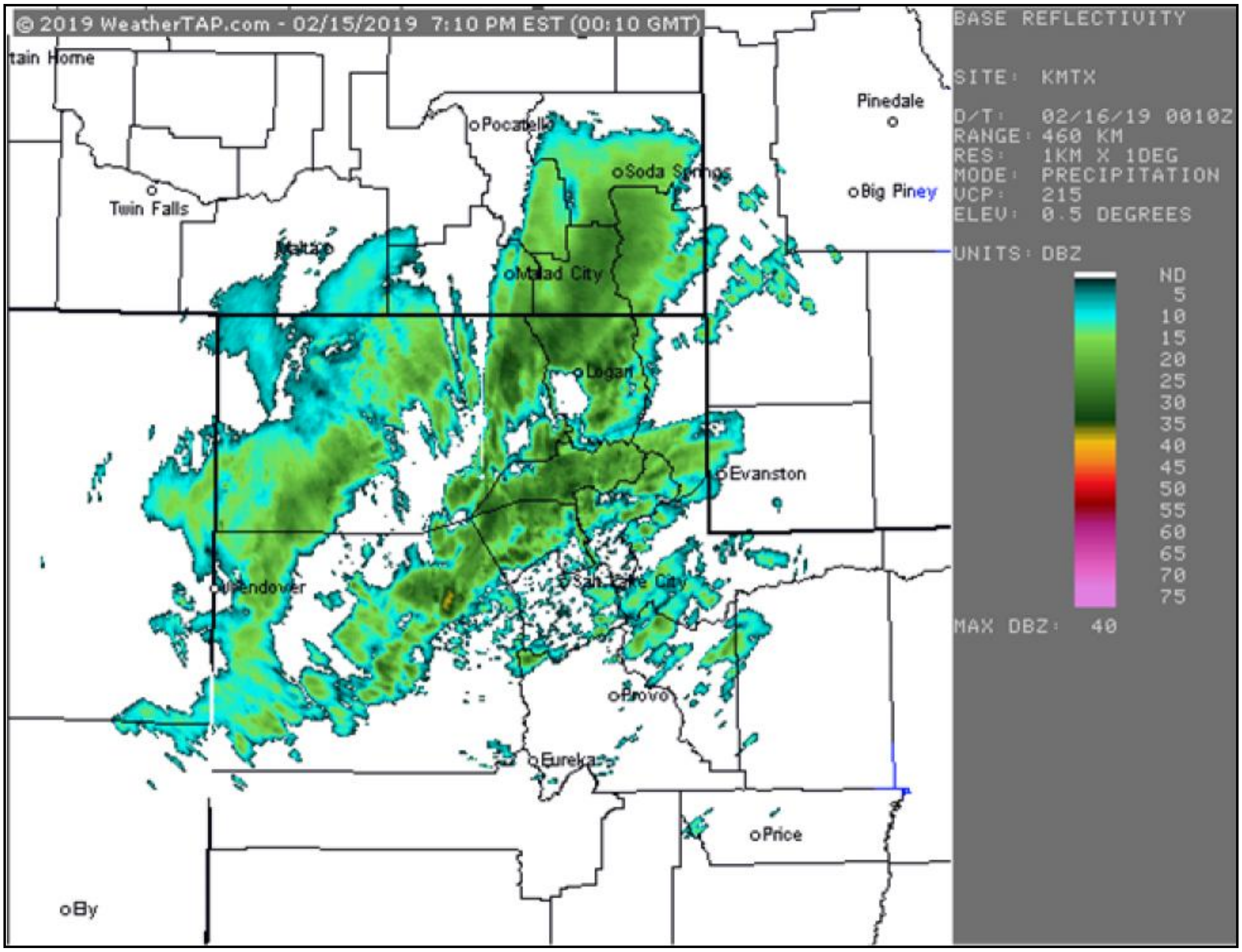


Figure 3.2 Weather radar image over northern Utah, on February 16 near the time of the satellite image in Figure 3.1

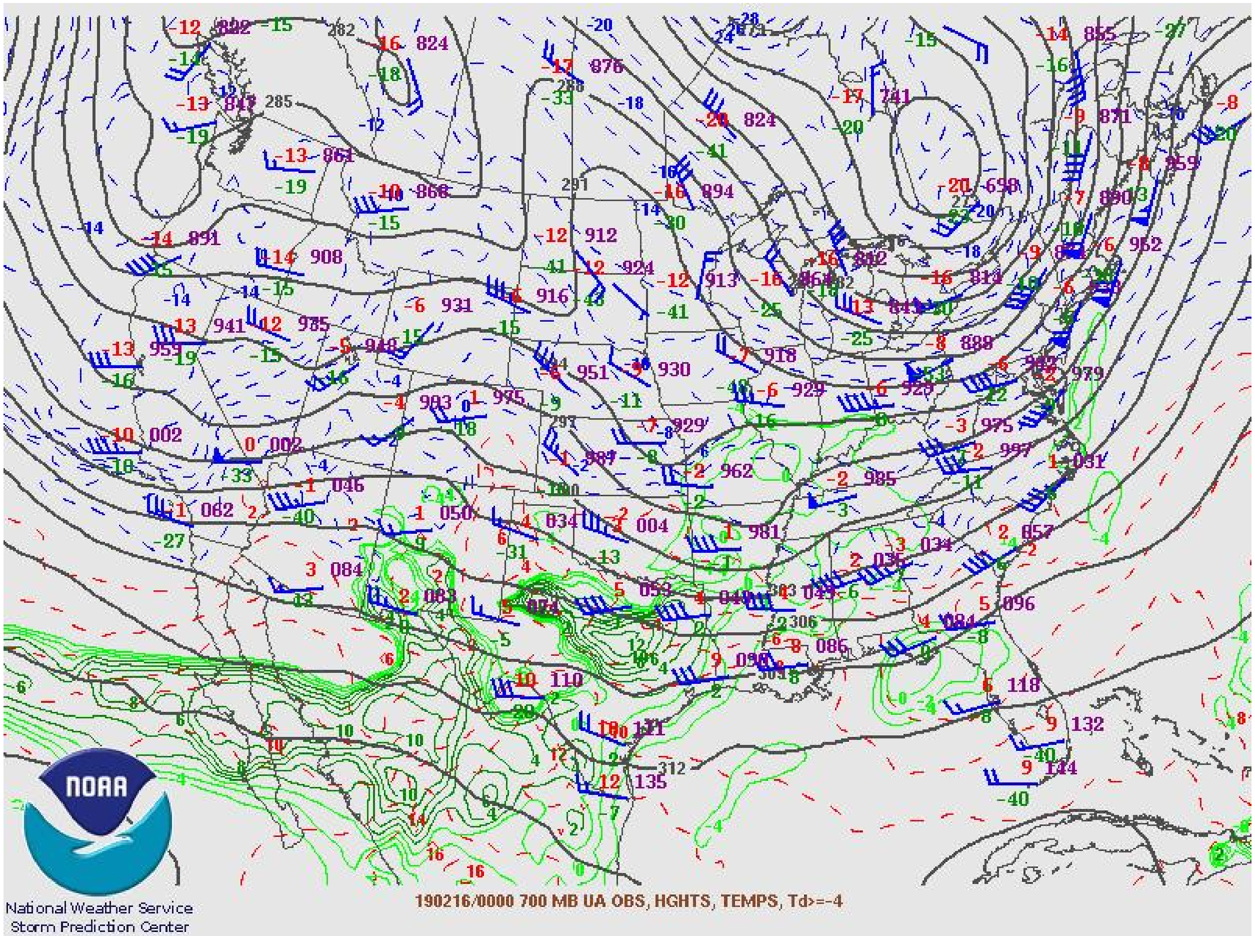


Figure 3.3 U.S. 700 mb map on February 16, corresponding to the time of Figures 3.1 and 3.2 near 1600 MST

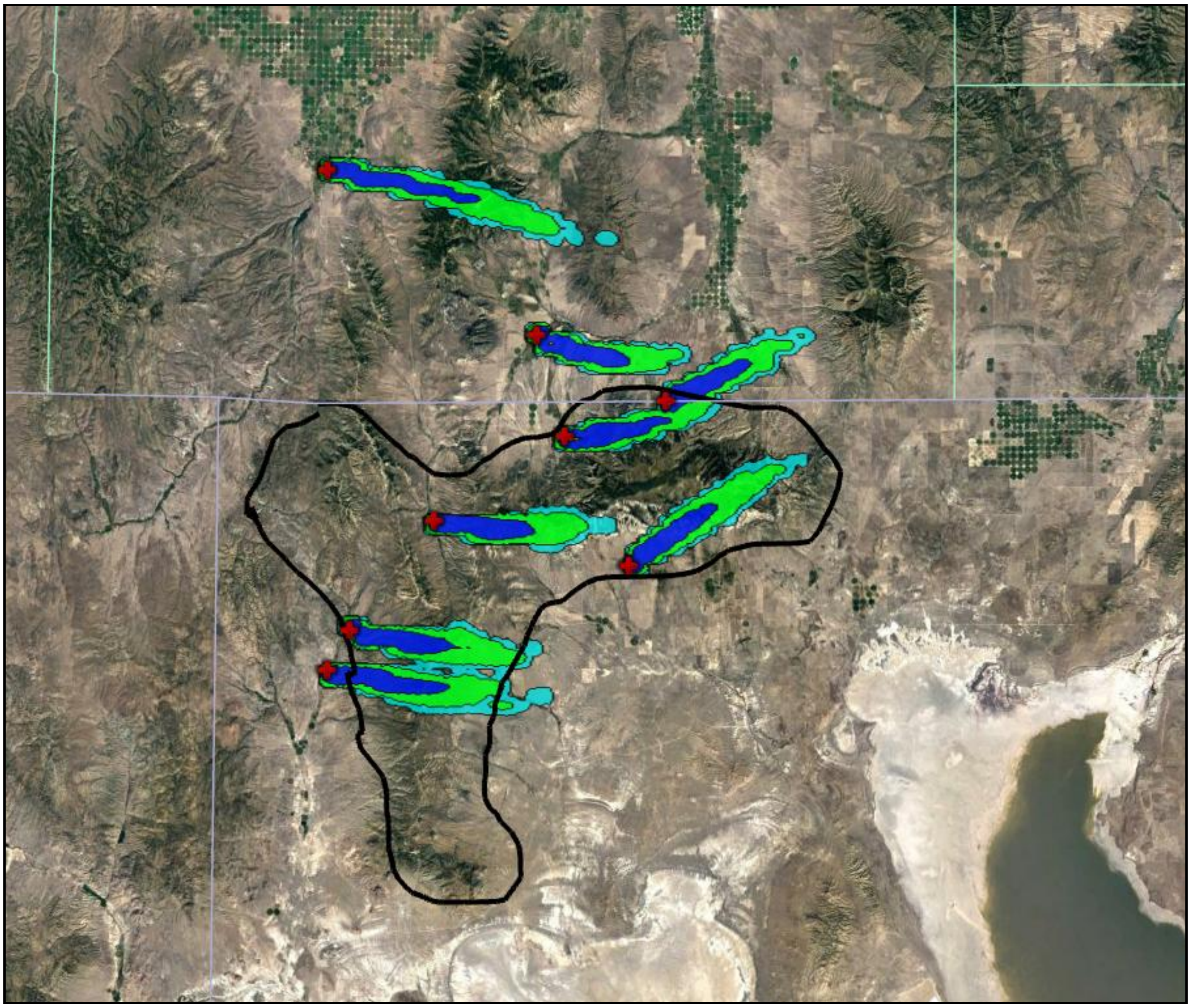
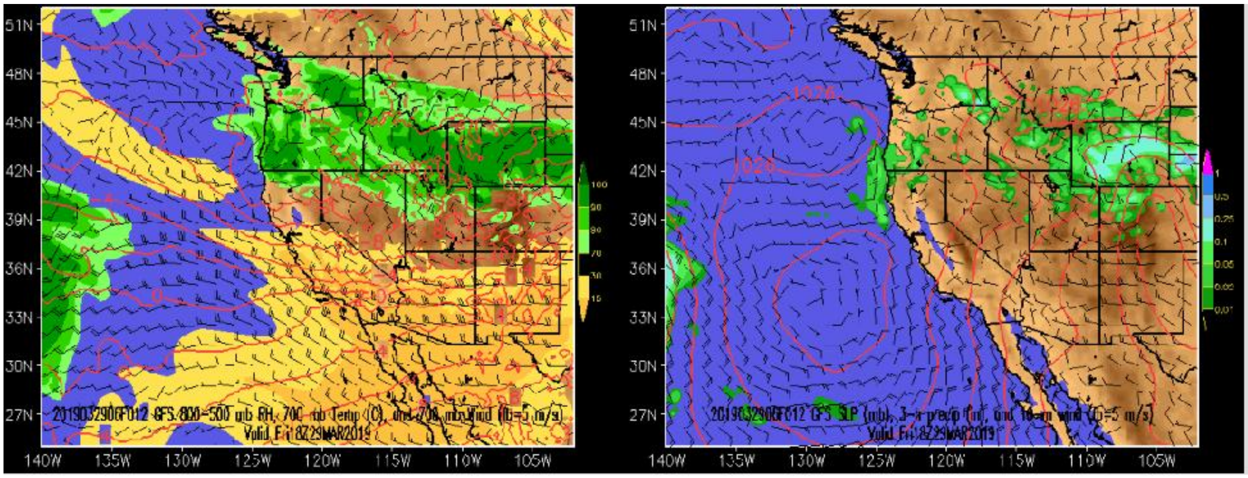


Figure 3.4 HYSPLIT plume dispersion forecast for potential seeding sites for the northwestern Box Elder County area on February 5. These plots show dispersion forecasts for potential seeding locations (only some of which are typically used in a given event).



Figures 3.5 GFS (Global Forecasts Systems) model plot during a storm event on March 29. 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.

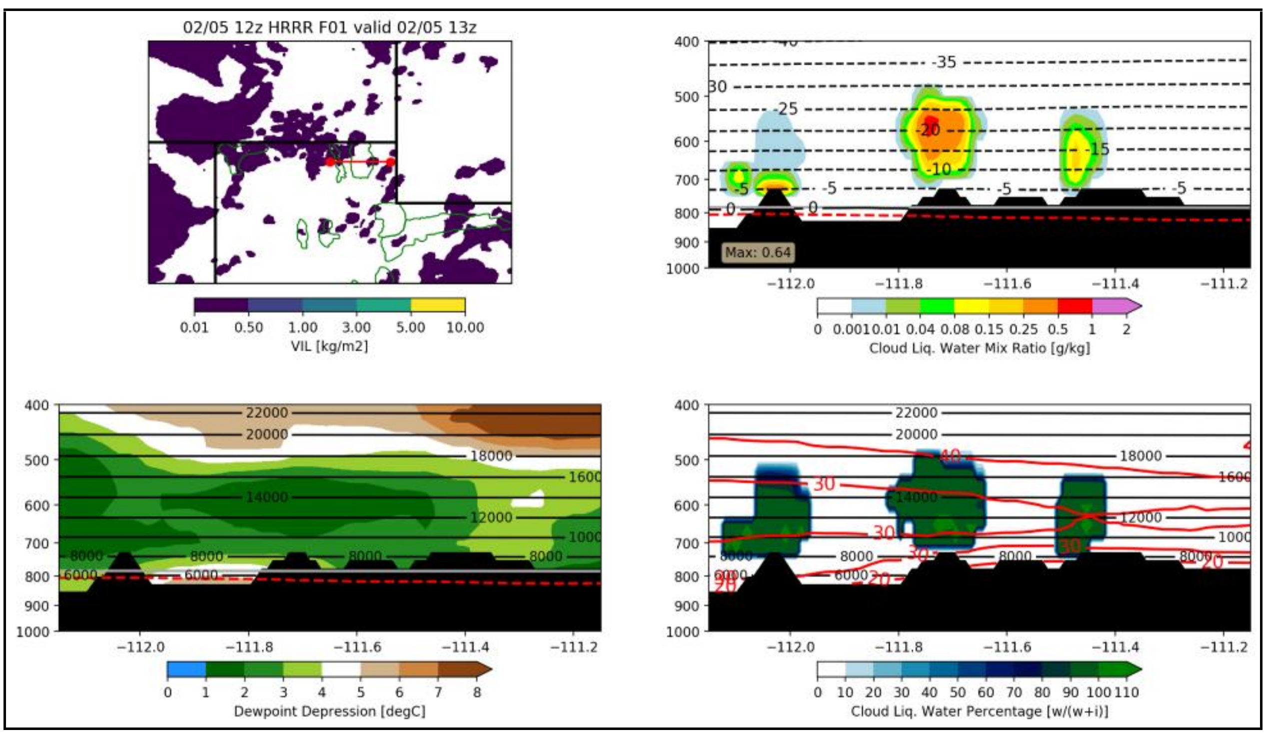


Figure 3.6 Data displays from the HRRR model: cross-section location and vertically integrated liquid (upper left); cross section of cloud liquid water and temperature (upper right); dew point depression, i.e. moisture saturation (lower left); and a plot of liquid vs. ice (lower right).

4.0 OPERATIONS

The 2018-2019 seeding program in Box Elder and Cache Counties began on December 1, 2018 and ended on March 31, 2019. During the four-month season, there were 17 seeding operations conducted on portions of 29 days. Five storms were seeded in December, three in January, three in February, and six in March. A cumulative 2,051.75 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 Table 4-2 shows seeding times for individual generator sites. Figure 4.1 is a graph of seeding operations (CNG usage) this season.

Precipitation was somewhat above normal in northern Utah during the 2018-2019 winter season, although closer to normal than in much of Utah which measured well above normal values. Snowpack in the Bear River Basin on April 1, 2019 averaged 115% of normal (median), with about 108% 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 4-3 provides average April 1 snowpack water content average for the Bear River drainage.

Table 4-1
Storm Dates and Number of Generators Used,
2018-2019 Season

Storm No.	Date(s)	No. of Generators Used	No. of Hours
1	December 12	14	78.25
2	December 18-19	12	123.5
3	December 25-26	3	34
4	December 27	9	13.5
5	December 30-31	15	283.25
6	January 6-7	11	113.5
7	January 17-18	17	300.75
8	January 21	4	25.25
9	February 3-5	23	323
10	February 10	12	58.75
11	February 15-16	14	206.5
12	March 6-7	6	98.25
13	March 8	13	118
14	March 12-13	3	36
15	March 22	2	9.5
16	March 23-24	6	91.5
17	March 28-29	7	138.25
Season Total	---	---	**2,051.75**

Table 4-2a
Generator Hours – Northern Utah, 2018 – 2019
Storms 1-10

Storm	1	2	3	4	5	6	7	8	9	10
Dates	Dec 12	Dec 18-19	Dec 25-26	Dec 27	Dec 30-31	Jan 6-7	Jan 17-18	Jan 21	Feb 3-5	Feb 10
SITE										
1-1										
1-3	4				9.5		16		8	
1-4					9.5					
1-5	4						16.25		8	
1-6	4						16		8	
1-7										
1-8	3.5				9.5		16.25		6.75	
1-9									42	
1-10	4.5									5
1-11										
1-12							18.75		4.5	
1-13	5.25	10		1.5	22		18.75		5.5	5
1-14		10		1.5	19					5
1-15	2.5	10		1.5	21.25	6.76	18.75		5.75	5
1-16		11.5			21.5	6			6	5
1-17						2	18.75		6	5
2-1	5.5	10		1.5			18		5	5
2-2	4.5	12		1.5	21.5		18		5	5
2-3		10			21.5				5.25	
2-4	7.5	10		1.5	21.75		18		5.25	4
2-5	9.5	10			20	6.75	18	6.5	5.25	4.75
2-7		10			21.5		17.5		4	
2-8	8		12	1.5	21.5	7	17.75	6.5	5.5	5
2-9			12		21.5		17.75	5.75	21.25	

Storm	1	2	3	4	5	6	7	8	9	10
Dates	**Dec 12**	**Dec 18-19**	**Dec 25-26**	**Dec 27**	**Dec 30-31**	**Jan 6-7**	**Jan 17-18**	**Jan 21**	**Feb 3-5**	**Feb 10**
SITE										
2-10	7		10			17	18.5		26.5	
2-11	8.5	10		1.5		17		6.5	5.5	5
2-12						17			29.25	
3-3						10			27.25	
3-6						11			19.5	
3-7						13			53	
3-8		10		1.5	21.75		17.75		5	
Storm	**78.25**	**123.5**	**34**	**13.5**	**283.25**	**113.5**	**300.75**	**25.25**	**323**	**58.75**

Table 4-2b
Generator Hours – Northern Utah, 2018 – 2019
Storms 11-17

Storm	11	12	13	14	15	16	17	Site Totals
Dates	Feb 15-16	Mar 6-7	Mar 8	Mar 12-13	Mar 22	Mar 23-24	Mar 28-29	
SITE								
1-1								0
1-3			7.5					45
1-4			3.75					13.25
1-5	4.25							32.5
1-6	4.25							32.25
1-7								0
1-8			6.75			13		55.75
1-9	4.25							46.25
1-10								9.5
1-11	22							22
1-12	16.25							39.5
1-13	16.75		11.5				21.75	118
1-14			8				19.75	63.25
1-15	16.5	15.5	11				22	136.5
1-16	16.5							66.5
1-17							11.75	43.5
2-1	18							63
2-2	18		4.5					90
2-3						10.75		47.5
2-4	17		11			21.25	20	137.25
2-5	18	16		12		21.25	21.5	169.5
2-7			11.25					64.25
2-8				12		9.75	21.5	128
2-9	17.75	16	10.5	12	4			138.5

Storm	11	12	13	14	15	16	17	Site Totals
Dates	**Feb 15-16**	**Mar 6-7**	**Mar 8**	**Mar 12-13**	**Mar 22**	**Mar 23-24**	**Mar 28-29**	
SITE								
2-10		16	8.75		5.5	15.5		124.75
2-11			11.5					65.5
2-12		16						62.25
3-3								37.25
3-6								30.5
3-7		18.75						84.75
3-8	17		12					85
Storm	**206.5**	**98.25**	**118**	**36**	**9.5**	**91.5**	**138.25**	

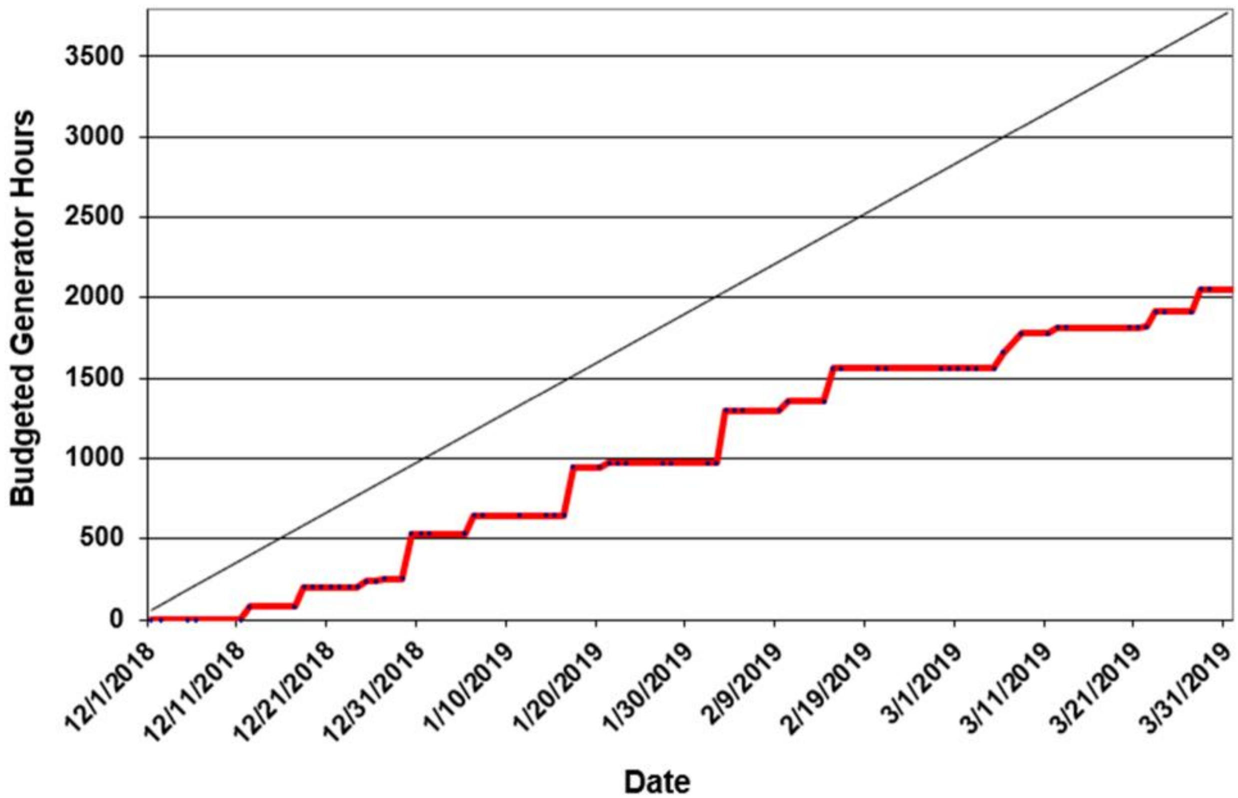


Figure 4.1 **Seeding operations during the 2018-2019 season (red), compared with a linear usage of total budgeted hours (diagonal black line).**

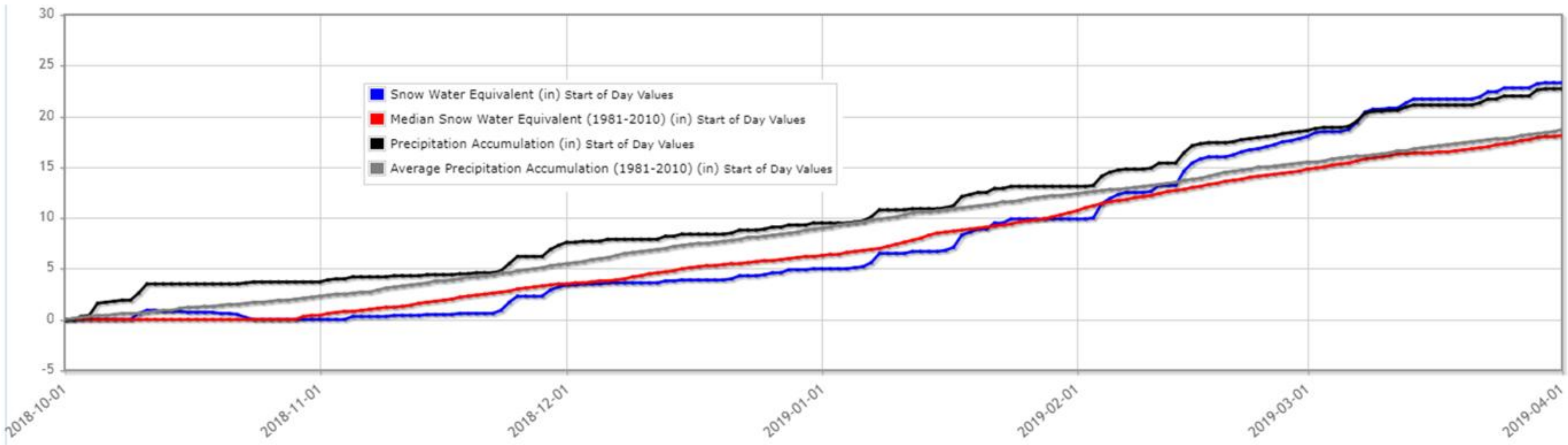


Figure 4.2 SNOTEL snow and precipitation plot for October 1, 2018 through April 1, 2019 for Bug Lake, UT. Smoothed lines are the corresponding normals.

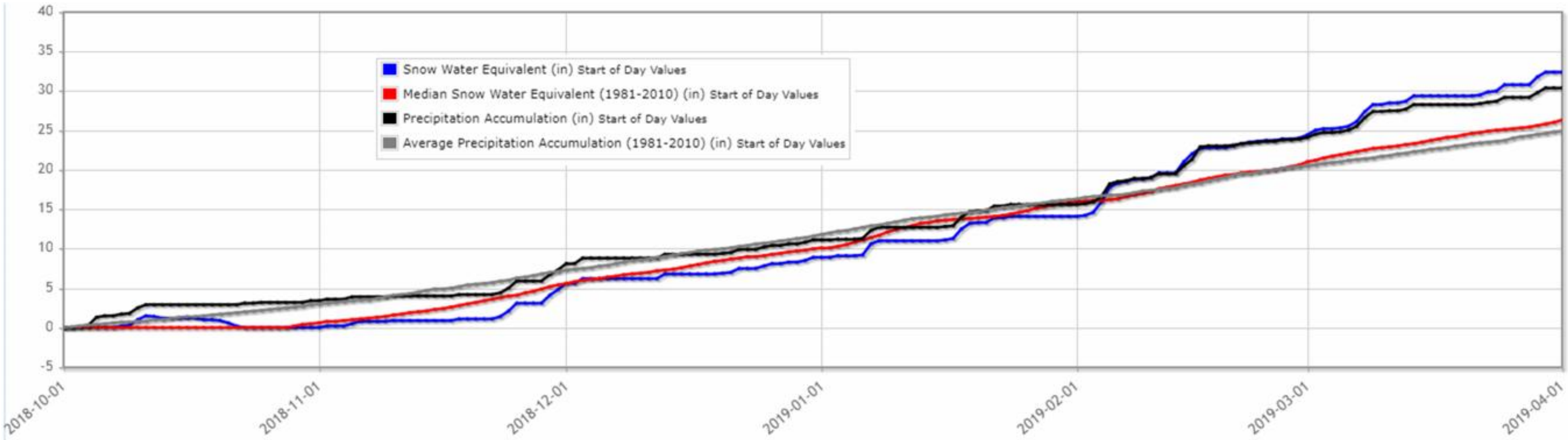


Figure 4.3 SNOTEL snow and precipitation plot for October 1, 2018 through April 1, 2019 for Monte Cristo, UT. Smoothed lines are the corresponding normals.

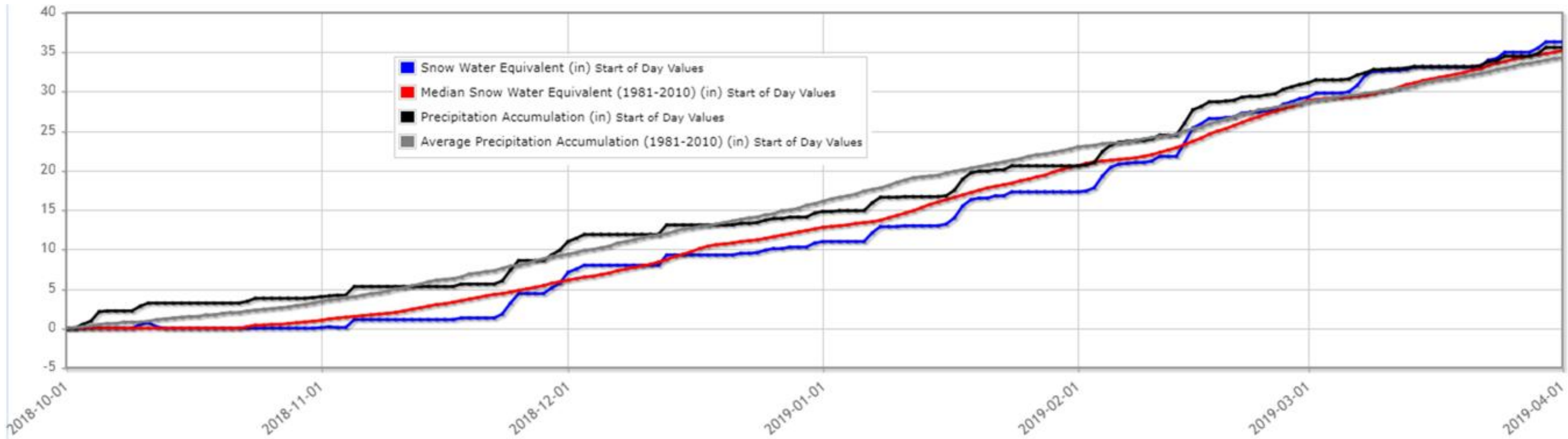


Figure 4.4 SNOTEL snow and precipitation plot for October 1, 2018 through April 1, 2019 for Tony Grove Lake, UT. Smoothed lines are the corresponding normals.

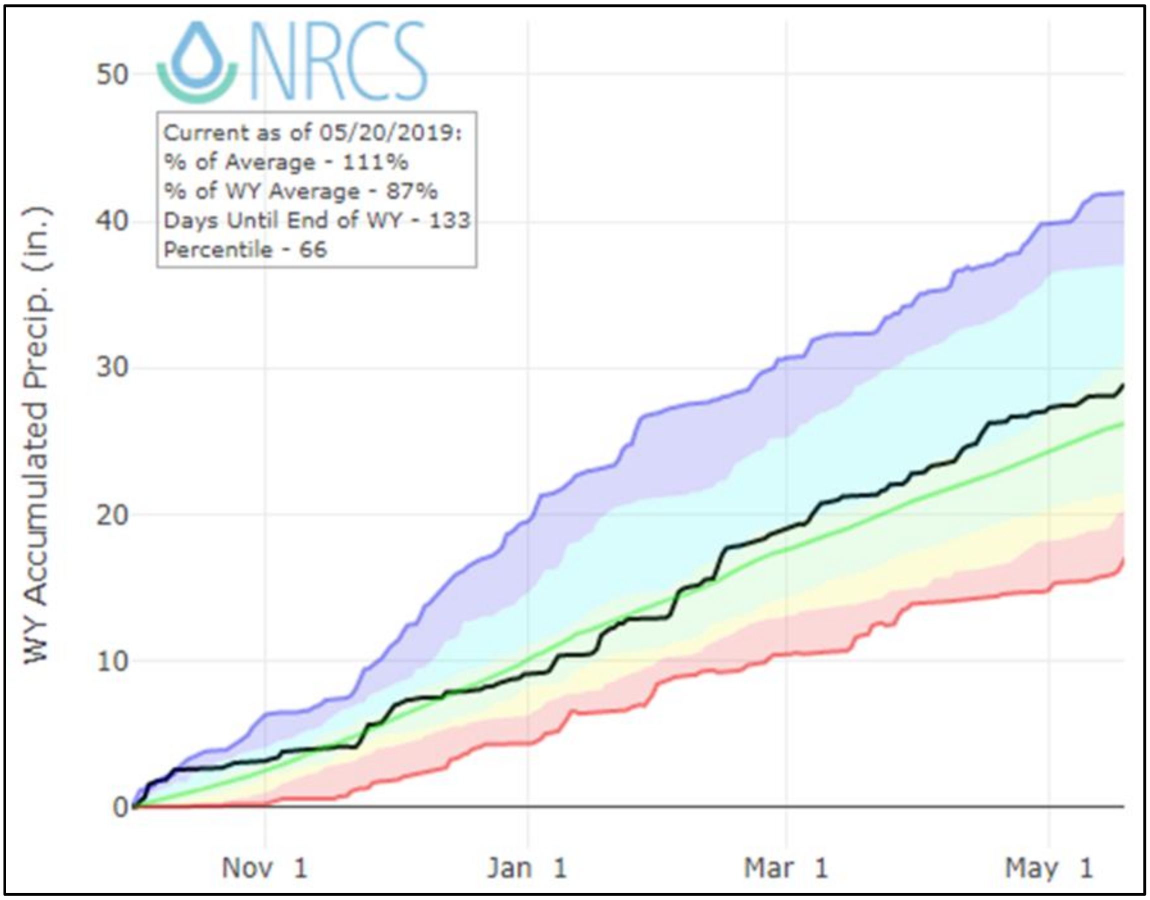


Figure 4.5 **SNOTEL accumulated precipitation plot (from NRCS) for the current water year, compared to average and max/min values, in the Bear River Basin; black line represents the 2019 water year through mid-May.**

Table 4-3
April 1, 2019 Percent of Normal Snowpack and Water Year Precipitation

Basin/Drainage	**April 1 Percent of Median Snow Water**	**April 1 Percent of Mean Water Year Precipitation**
Bear River	115%	108%

Figures 4.6 – 4.9 show monthly precipitation as a percent of normal during the project period for Utah and western Colorado.

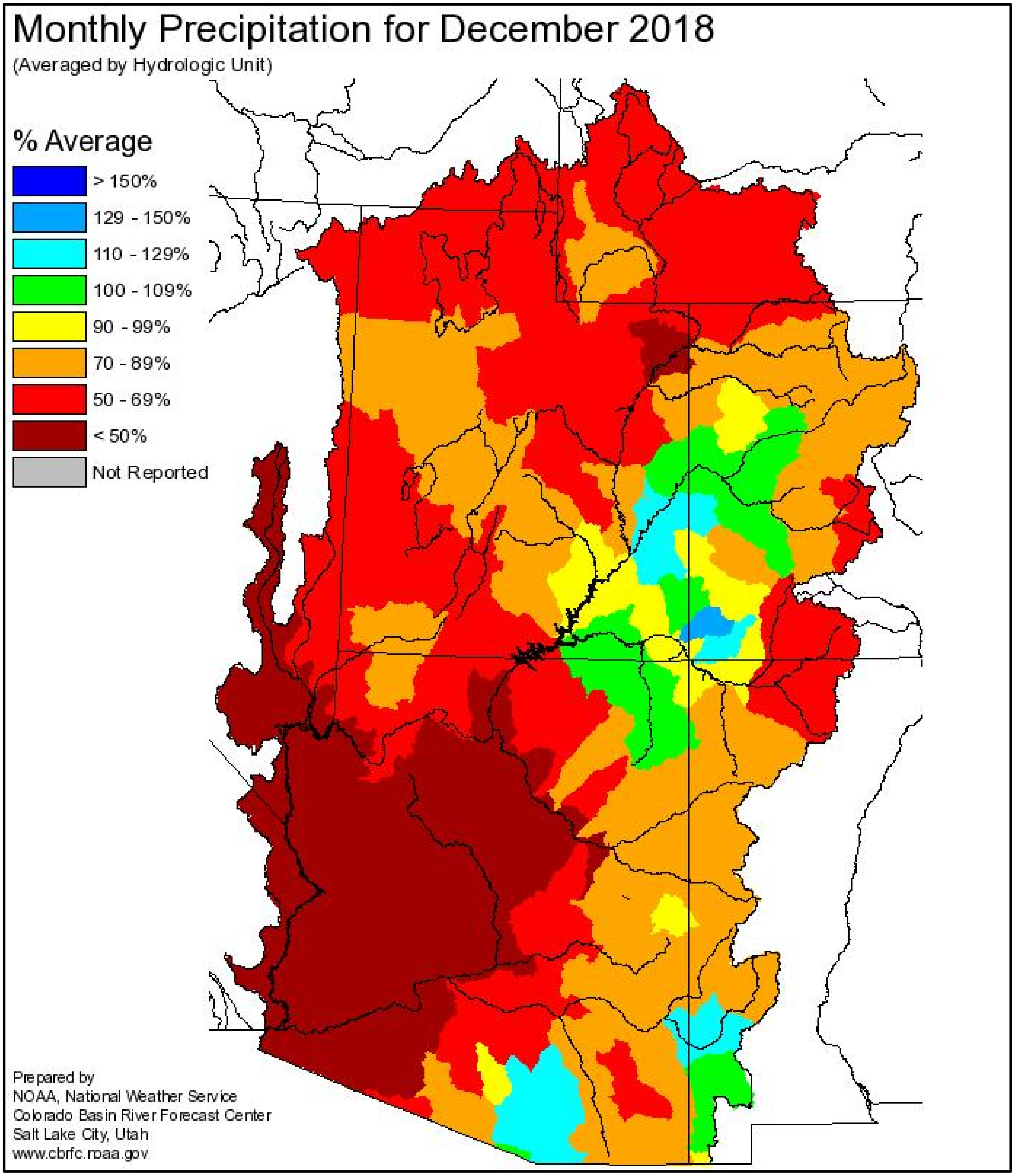


Figure 4.6 December 2018 precipitation, percent of normal

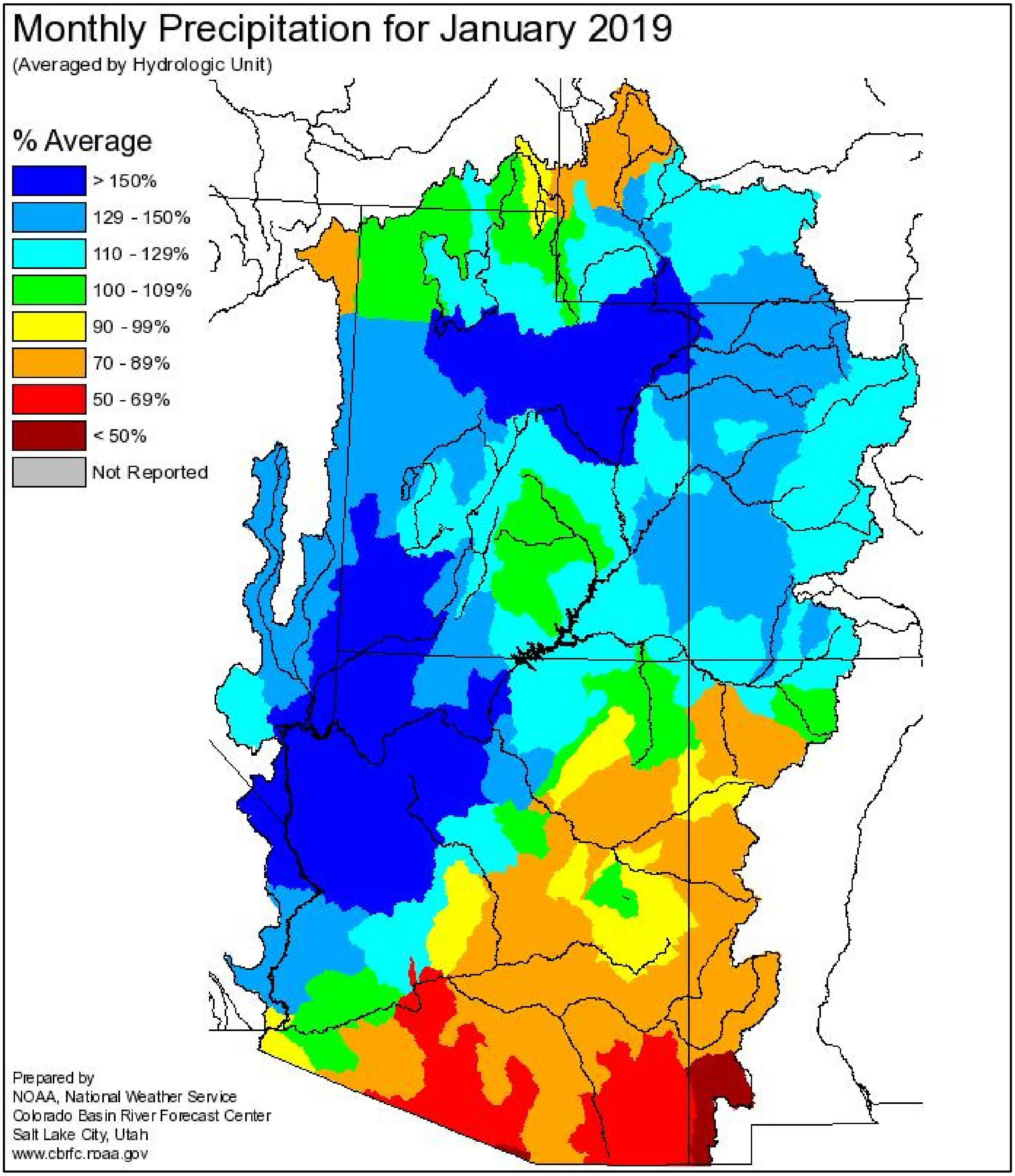


Figure 4.7 January 2019 precipitation, percent of normal

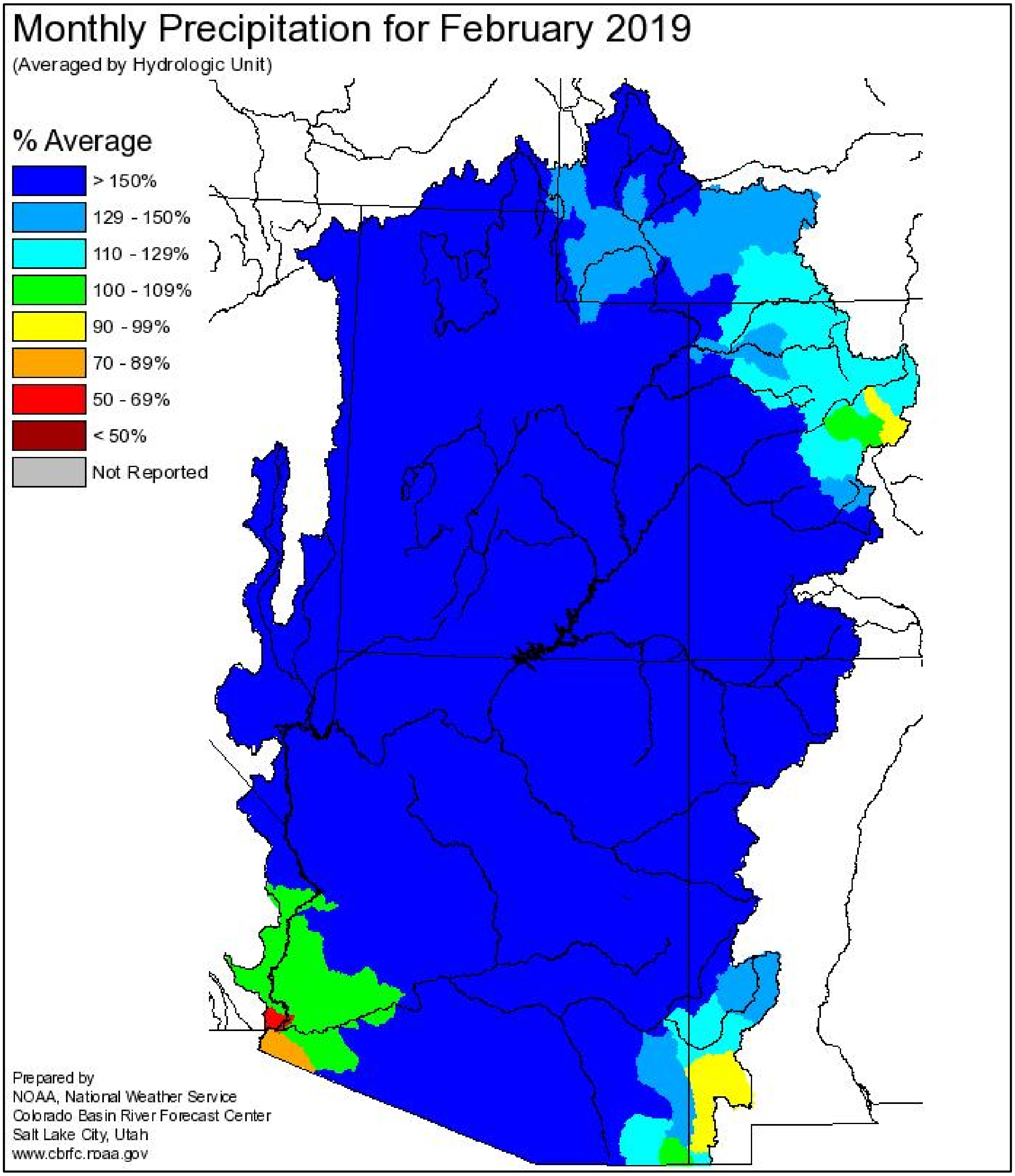


Figure 4.8 February 2019 precipitation, percent of normal

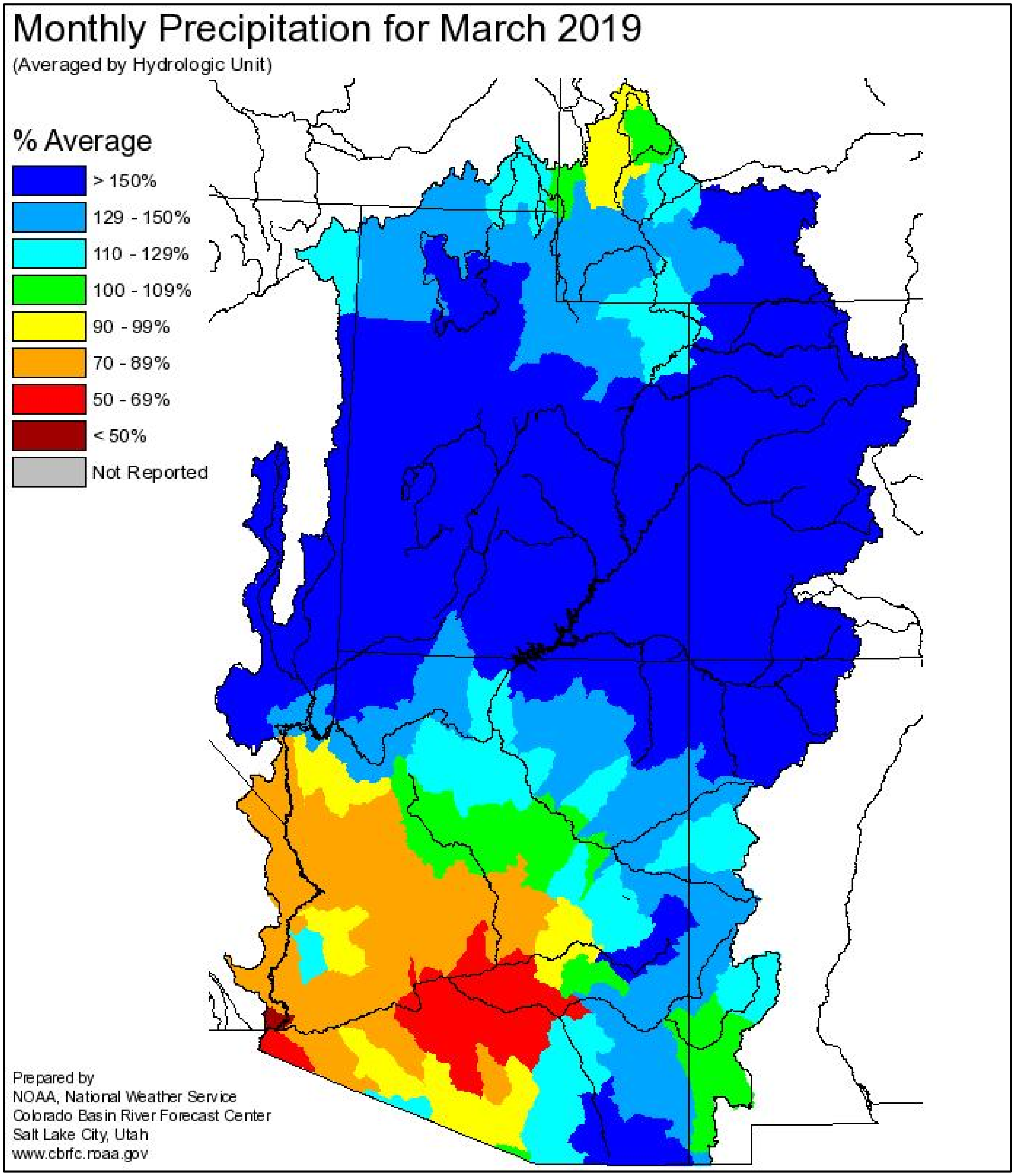


Figure 4.9 March 2019 precipitation, percent of normal

4.1 Operational Procedures

In operational practice, 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 Table 2-1 of the previous section, and if no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators was ignited and adjusted as conditions required. Monitoring and seeding continued as long as conditions were favorable and precipitating clouds remained over the target area. In a typical sequence of events, certain generators would be used in the early period of the storm passage, some of which might be turned off as the wind direction changed, with other generators then used to target the area in response to the evolving meteorological conditions. Some generator sites, due to their location, can be used in a wider variety of wind flow situations than others, and thus are used more often.

4.2 Operational Summary

A brief synopsis of seeded (or otherwise significant) storm events during the operational seeding period is provided below. All times reported are local (MST/MDT).

December 2018

December was a fairly normal month across the area, although there were some significant dry periods during early and mid-December which resulted in slightly below normal monthly precipitation and snowfall for the month as a whole. Most December storm activity and seeding operations occurred during the latter portion of the month, with five total seeded storm events in December.

A vigorous, fast-moving trough brought the first seeding opportunity of the season on December 12. A strong valley temperature inversion and associated low stratus deck was in place initially, so seeding operations did not begin until this inversion had broken by about midday. Following this, some excellent conditions developed during the afternoon and seeding was conducted during the afternoon and early evening hours, with some good orographic and even weak convective cloud elements. The 700-mb temperature dropped to around -12 C during the afternoon hours in northwesterly flow. Clearing was forecast overnight and seeding ended in the evening. SNOTEL observations indicated totals generally in the 0.4 – 0.8" range water equivalent.

A trough crossed the area on the night of December 18-19, helping to mix out temperature inversions that had previously re-developed. Seeding was conducted to affect eastern portions of the target area overnight, ending on the morning of the 19th with drying conditions. The 700-mb temperature dropped to around -8 C, and some nice looking orographic clouds were noted on the morning of the 19th near the tail end of the event. SNOTEL data indicted amounts of about 0.1 – 0.4" of water.

Several weak systems affected northern Utah during the December 20-24 period, but were not conducive to seeding due to low level stability, temperatures, or other factors. However, a somewhat better system provided a minor seeding opportunity on the night of December 25-26 as the 700-mb temperature dropped to around -10 C. Seeding ended early on the 26th with drying conditions. SNOTEL data showed about a quarter to half inch of water equivalent with this latter event.

A cold system moving in from the north resulted in brief seeding operations on the morning of December 27, although temperatures were cooling to near/below -15 C at 700 mb and it was soon determined that the clouds appeared to be essentially all in the ice phase and thus not particularly suitable for cloud seeding. This resulted in the termination of operations. Precipitation was on the light side with around a quarter inch of water equivalent at some sites.

A more significant seeding opportunity occurred beginning on December 30, with widespread snowfall and indications of more significant SLW in this system. Seeding began by midday, with widespread seeding operations that continued overnight (Dec 30-31) in some areas. The 700-mb temperature was near -12 C with winds becoming northwesterly for most of this time period. Seeding ended on the morning of December 31, with colder, windy and generally drying conditions. There were indications of around a half inch or so of water equivalent in this event.

January 2019

There were some dry periods in January, but also some very significant storm periods which kept the month as a whole near normal in terms of snowfall in northern Utah. There were three seeded storm periods in January, one of which was particularly significant in terms of the amounts of seeding conducted.

A moist storm event began on the night of January 6-7 and continued through much of the day on the 7th. Winds began as southerly overnight with limited seeding operations, then more westerly and finally northwesterly on the 7th with an expansion of operations. The 700-mb temperature was near -8 C. Snowfall and seeding ended by about 1500 MST on January 7. This was a productive event with over an inch of water equivalent in most target areas and as much as 2 inches of water equivalent at some sites.

A strong and moist weather system brought copious precipitation to northern Utah on January 17, continuing overnight. Strong southerly winds and warm temperatures, above -5 C at 700 mb, precluded seeding initially. However, seeding began during the afternoon hours in Box Elder County and was soon initiated for eastern portions of the target as well. Seeding continued overnight as well, in northwesterly flow with good orographic effects over portions of the target area. Widespread seeding was conducted during this time period, although it ended early on the 18th as skies were clearing. SNOTEL data showed about 2-3" of water equivalent at many sites from this event.

A limited seeding opportunity occurred in northwesterly flow on January 21, as winds turned northwesterly with some light precipitation and temperatures dropped to below -5 C at 700 mb. A few sites in the Logan area were utilized to seed eastern portions of the target area, although conditions were somewhat marginal. Precipitation amounts were on the light side, generally from about a tenth to a half inch.

February 2019

February was a wet month as a whole, thanks in large part to a couple of very significant precipitation periods during the month. Portions of these contained subtropical moisture and were on the warm side for seeding, but some very good seeding opportunities were realized. There were three seeded storm periods in February.

Periods of orographic and some convective precipitation moved through the area during the February 3-4 period, with the 700-mb temperature around -7 to -8 C, followed by a cold front early on February 5 which was followed by a much colder and drier air mass. Seeding began on February 3 and continued from suitable sites, with a vast majority of available sites utilized during this storm period. Good orographic, and some convective, precipitation was observed via radar images. Seeding operations ended by later on February 5, as the remaining cloud deck appeared to be essentially all ice. This storm period (February 3-5) was very beneficial, with precipitation amounts of 3-4” observed at many SNOTEL sites. It also had more total seeding than any other event this season, with a total of 323 generator hours.

A strong cold frontal passage affected Utah on February 10, with very cold air (to -17 C or colder at 700 mb) behind the front. Seeding was conducted with a precipitation band that moved through the area during the afternoon to the early evening hours. Seeding ended during the evening as temperatures became very cold overnight. This frontal passage brought about a quarter to half inch of water to most of the target areas.

A large plume of tropical/subtropical moisture moved across the area on February 13-14, with widespread precipitation and warming temperatures initially. The 700-mb temperature warmed to about -2 C on the 14th, with widespread precipitation over the area. However, a trough brought cooling to the area beginning on February 15 and seeding was conducted during the afternoon/evening, continuing overnight for eastern portions. The 700-mb temperature became fairly cold, falling to near -14 C by early on February 16. Seeding operations ended by mid-morning on the 16th as skies were clearing. Precipitation totals for the February 13-16 period as a whole were quite impressive, the amounts from 3-4+ inches at many SNOTEL sites. However, the colder (seeded) portion of the system was represented by totals closer to an inch of water at most sites.

March 2019

March was an active weather month with near to above normal precipitation, thanks to some major storm periods early in March and again toward the end of the month. There was a total of six seeded storm periods in March.

A trough moved from California across the Great Basin during the March 6-7 period, with temperatures cooling sufficiently for operations beginning the night of March 6. The 700-mb temperature cooled to about -7 C by the morning of the 7th, and seeding operations were conducted during this period from several sites. Showers were decreasing by midday and seeding was terminated then. Precipitation totals were significant in some areas, with an inch or more of water equivalent as of March 7. Close on its heels, another trough brought colder air to the region on March 8 and conditions were favorable for somewhat more widespread seeding operations during the daytime hours. Seeding began again on the morning of March 8, with widespread precipitation over the area. By mid-afternoon, showers were decreasing and seeding operations ended. The March 8 system produced an additional 2" of more of water equivalent at many SNOTEL sites, for totals of around 3" or locally more for the entire March 6-8 period.

Seeding was conducted from a few sites on the night of March 12-13 as a fairly minor frontal system crossed the area. The 700-mb temperature dropped to around -12 C by the 13th, and seeding ended in the morning as precipitation was widely scattered. This system brought fairly light amounts, generally a half inch or less to most areas.

Some light showers developed over the area, mostly from a higher cloud deck on March 22. A couple of seeding sites were activated briefly, but conditions proved to be too marginal. Another weak system over the Great Basin produced more widespread convective showers across northern Utah on March 23-24 with a generally southeasterly wind pattern. The wind direction limited seeding operations, but seeding was conducted from several sites. Most of the convective showers, as well as seeding operations, ended by sunset on the 24th. Precipitation totals during the March 22-24 period as a whole amounted to an inch or locally two in portions of the target areas.

A trough centered along the coast sent a few waves of orographic and convective type precipitation across northern Utah on March 28-29. The 700-mb temperature ranged from about -4 to -8 C, with fairly widespread precipitation in southwesterly to northwesterly flow. Seeding operations began on the evening of March 28 and continued until the evening of the 29th, following a cold frontal passage. Precipitation totals of 1-2" of water equivalent were widespread during the March 28-29 period. This was the final seeded period of the season.

5.0 ASSESSMENT OF SEEDING EFFECTS

5.1 <u>Background</u>

The task of determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program for an individual season is rather difficult, and the results should be viewed with appropriate caution. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area, and between areas, from season to season. The ability to detect a seeding effect becomes a function of the magnitude of the seeding increase and the number of seeded events, compared with the natural variability in the precipitation pattern. Larger seeding effects can be detected more easily, and with a smaller number of seeded cases than required to detect smaller increases.

Historically, the most significant seeding results have been observed in wintertime seeding programs in mountainous areas. However, the apparent differences due to seeding are relatively small, being generally of the order of a 5-15 percent seasonal increase. In part, this relatively small percentage increase accounts for the significant number of seasons required to establish these results with any certainty, often five or more years.

Despite the difficulties involved, some techniques are available for estimation of the effects of operational seeding programs. These techniques are not as statistically rigorous or scientifically desirable as is the randomization technique used in research, where roughly half the sample of storm events is randomly left unseeded. However, most project sponsors do not wish to forego half the potential benefits of a cloud seeding project in order to better document the effects of the cloud seeding. The less rigorous techniques do, however, offer a reasonable indication of the long-term effects of seeding on operational programs, without foregoing half the seeding opportunities.

A commonly employed technique, the one utilized by NAWC in this assessment and in evaluation of its other winter seeding projects, is a "target" and "control" comparison. This technique is described by Dennis (1980) in his book entitled "Weather Modification by Cloud Seeding". The technique is based on selection of a variable that would be affected by seeding (such as precipitation or snowpack). Records of the variable to be tested are acquired for an historical period of many years duration (20 years or more if possible). These records are partitioned into those located within the designated "target" area of the project and those in a nearby not-seeded "control" area. Ideally the control sites should be selected in an area meteorologically similar to the target, but one which would be unaffected by the project seeding (or seeding from other adjacent projects). The historical data in both the target and control areas are taken from past years that have not been subject to cloud seeding activities. These data are evaluated for the same seasonal period of time (e.g., months) as that when the seeding is to be or has been conducted. The target and control sets of data for the unseeded seasons are used to develop an equation (typically a linear regression), which predicts the amount of target area precipitation, based on precipitation observed in the control area. This regression equation is then used during the seeded period to estimate what the target area precipitation would have been without seeding, based on that observed in the control area. This allows a comparison to be made between the predicted target area natural precipitation and what actually occurred during the seeded period, to look for any differences potentially caused by seeding activity.

This target and control technique works well where a good historical correlation can be found between target and control area precipitation. Generally, the closer the target and control areas are geographically, and the more similar they are in terms of elevation, the higher the correlation will be. Control areas selected too close to the target, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect in the target area. For precipitation and snowpack assessments, a correlation coefficient (r) of 0.90 or better would be considered excellent. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set would be explained by the regression equation used to predict the subject variable (expected precipitation or snowpack) in the seeded years. An equation indicating perfect correlation would have an r value of 1.0.

Experience has shown that it is virtually impossible to provide a precise assessment of the effectiveness of cloud seeding over one or two winter-spring seasons. However, as the data sample size increases, it becomes possible to provide at least a reasonable estimate of seeding effectiveness.

5.2 Some General Considerations in the Development of Target/Control Evaluations

The number of surface observing sites operated by agencies such as the NRCS, especially snow course sites, has been gradually reduced. Even some cooperative observer sites, which are managed by the National Weather Service, have either been discontinued or have become inactive. Therefore, the selection of target and control sites first involves examination of the period of record of data at a given location, and changes to the set of target or control sites are sometime necessary in the event that measurements at a site are discontinued.

There have been, and continue to be, multiple cloud seeding programs conducted in the State of Utah. As a consequence, well-correlated potential control areas that are truly unaffected by cloud seeding are somewhat limited in availability. This is complicated by the fact that the best correlated control sites are generally those closest to the target area. Many measurement sites in the northern part of the state, although not located within the boundaries of the intended area of effect of a seeding program, have been subjected to potential effects of numerous historical and current seeding programs. This renders such sites of questionable value for use as controls. Thus, control sites for evaluation of the northern Utah seeding program are located in areas of southern Idaho and northeastern Nevada 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 is to look for sites upwind or crosswind from the target area 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. The effect of different upper airflow patterns and the attendant storm tracks often results in heavier precipitation in one area versus the other. For example, a strong El Niño pattern may favor the production of heavy winter precipitation in the southwestern United States while a strong La Niña pattern may likely result in below normal precipitation in that region.

Having control sites either side (crosswind) of the target area relative to the generalized flow pattern can improve the prediction of target area precipitation under these variable upper air flow pattern situations.

An additional consideration in the selection of control sites for the development of an historical target/control relationship is that of data quality. A potential control site may be rejected due to poor data quality or excessive 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. The double mass plot (an engineering analytical tool) may be used for inter-comparisons of station data, especially if a station has been moved during its history. This type of plot will indicate any changes in relationships between the two stations. If these changes (deflections in the slope of the line connecting the points) are coincident with station moves and they suggest a significant difference in the relationship, the site that was moved is excluded from further consideration.

There are two types of precipitation observations typically available from mountainous areas in the west: standpipe storage precipitation gages and snow pillows. With the advent of the Natural Resources Conservation Service's (NRCS) SNOTEL data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before the SNOTEL system was developed, these data had to be acquired by physically visiting the sites to make manual measurements. This is still required at some sites. Figure 5.1 is a photo of an NRCS SNOTEL site during the warm season, to allow the reader a better understanding of the two types of observation systems. The vertical tube is the standpipe storage gauge, which is approximately 12" in diameter. The storage gauges are approximately 20' in height, so that their sampling orifices remain above the snowpack surface. There are at least two types of problems associated with high elevation observations of the water equivalent of snowfall, as measured by standpipe precipitation storage gauges. These areas of potential concern include clogging at the top of the standpipe storage gauge, and blow-by of snowflakes past the top of the standpipe gauge. Either situation would result in an underestimate of the actual precipitation that had occurred. In the fall, the storage gauge is charged with antifreeze, which melts the snow that falls to the bottom of the gauge. A pressure transducer records the weight of the solution. The weight of the antifreeze is subtracted from the total weight to obtain the weight of the water, which is then converted into inches. Heavy, wet snow may accumulate around the top of the standpipe storage gauge, either reducing or stopping snow from falling into the standpipe and resulting in an underestimate of precipitation. Snow that falls with moderate to strong winds may blow past the top of the gauge, which can also result in an underestimate of precipitation. NRCS sites are normally located in small clearings in forested areas to help reduce the impacts of wind problems. Sites that are near or above timberline are more likely to be impacted by wind since sheltered sites may be difficult to find in these areas. The snow pillow, pictured on the pad at ground level in the foreground of Figure 5.1, is filled with antifreeze. This system weighs the snowpack, providing time-resolved records of the snowpack water content. Snow pillows can also have difficulty in providing accurate measurements of snow water content, because of wind either adding or removing snow from the measurement site when snow conditions are favorable for drifting.

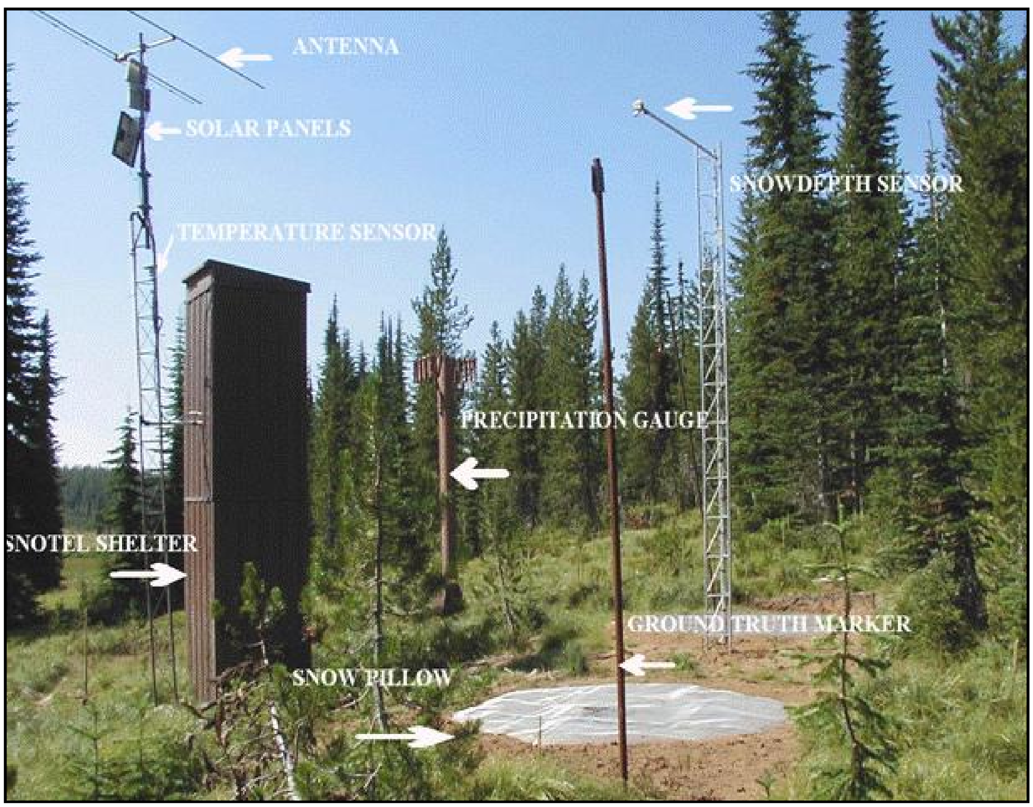


Figure 5.1 SNOTEL site photo

The bottom line is that it is difficult to accurately measure snow water equivalent at unmanned high-elevation sites. Both types of NRCS observations (gauge and snow pillow) can best be viewed as approximations of the actual amount of water that falls during a winter season. NRCS SNOTEL sites frequently provide the only type of precipitation observations available from the higher elevation areas that are targeted by winter cloud seeding programs. They are well suited for use in estimations of seeding effects, but interpretation of the indicated seeding effects must keep in mind the limitations of the measurement systems and their data.

5.3 Evaluation of Precipitation and Snowpack in the Target Areas

Experience has shown that it is virtually impossible to provide an accurate assessment of cloud seeding effects over one or two winter-spring seasons. However, as the data sample size increases, it becomes possible to provide at least a reasonable estimate of seeding effectiveness. Since there have been well over 20 seasons of cloud seeding in both project target areas, this technique should provide a reasonably good estimate of the results.

Using the target-control comparison described above, mathematical relationships for the variables (both precipitation and snowpack) were determined between a group of sites in the unseeded (control) area and the sites in the seeded (target) area. From these non-seeded data, predictor equations were developed. Then, the value of the variable observed in the unseeded (control) area was used to predict the value of the variable in the seeded (target) area in the absence of seeding. The difference between the predicted natural amount and the observed amount in the seeded area (target) is the excess, which may be the result of the seeding.

Historically, Utah has had snowpack measurements taken at (usually) monthly intervals for many years; and unlike many other states, precipitation measurements are also available from some of these same high elevation sites. Consequently, both precipitation and snow water measurements are available for more than 30 years of record from a large number of sites in Utah. Regression analysis has also been utilized to provide additional historical data for some Utah sites that had shorter records during the historical period. Likewise, regression analysis was used to provide additional estimated data at some sites in adjacent states (Arizona, Idaho, and Nevada) during the historical period for potential use as control sites.

Precipitation data used in the analysis were obtained from the NRCS and/or from the National Climatic Data Center, and represent the official published records of those organizations. Similar snowpack (water content) 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 Cache County. Evaluations in earlier years included precipitation sites in the Cache Valley, but it was decided in 1998 to restrict the evaluation to the higher elevation sites within the intended target area. This step was taken to more accurately estimate the impact of the cloud seeding program within the intended target area. There are no measurements made of precipitation using standpipe gauges in northwestern Box Elder County; therefore, analysis from that sensor type for that target area is not possible. However, snowpack analyses from snowcourses in the northwestern Box Elder target are included in the analyses.

5.3.1.1 Target Area Gauge Sites

The selected target sites extend in an arc 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 then arc 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.

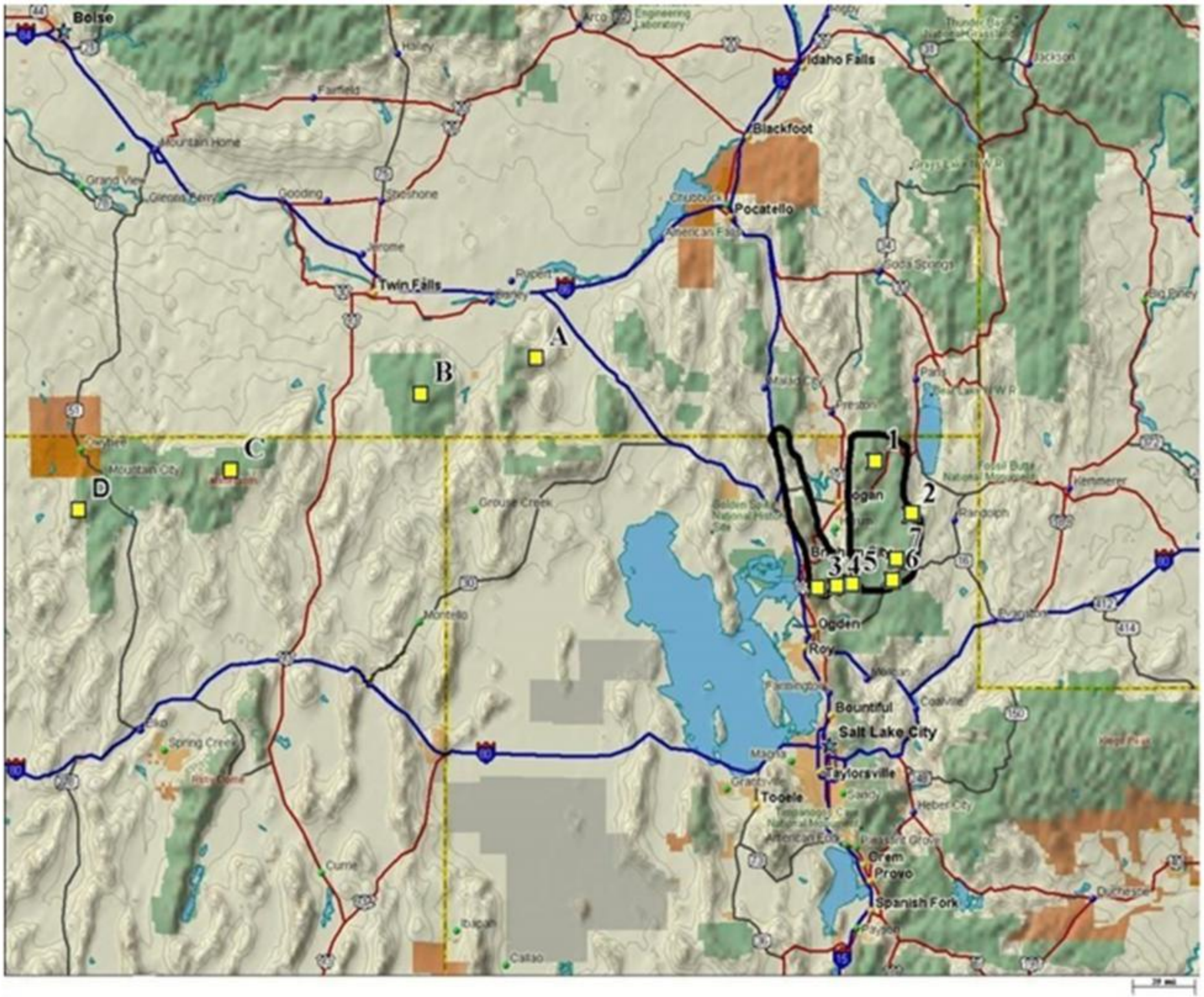


Figure 5.2 Precipitation gauge sites used in evaluation, eastern Box Elder and Cache Counties, with site data in Table 4-1. The target area is outlined in black. The target sites are numbered; the control sites have letter ID's.

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	42E 19'	113E 32'
B	Bostetter RS, ID	I14G01	7,500	42E 10'	114E 11'
C	Pole Creek RS, NV	N15H14	8,330	41E 52'	115E 15'
D	Fawn Creek #2, NV	N16H10	7,050	41E 49'	116E 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/snowcourse 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 during most of its history. Review of the seeding program showed that the December – March period has been prevalent through the program's history (not December – February, as was stated in some reports). 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 snowcourse data. Some estimation of monthly precipitation totals was necessary before about 1988, since after this time NRCS began replacing storage gauge sites (which required a manual reading) with automated SNOTEL sites. Since then, reliable monthly readings have been available from all the SNOTEL sites.

5.3.1.3 Regression Equation Development

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

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

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

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

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

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

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 (15.38 inches) for the December 2018 through March 2019 period was inserted in equation (1), the most probable average target area natural precipitation was calculated to be 19.82 inches using the linear regression technique. The average observed precipitation for the 7 gauges in the target group was 22.57 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 (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 1.14, or from (4), 14% more 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 30 seeded December-March periods (1989-2019 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 1.1 inches more than predicted during the seeded periods. Appendix B 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 49 water years, with the 19 water years from 1970 through 1988 representing the historical (unseeded) years and the remaining 30 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.

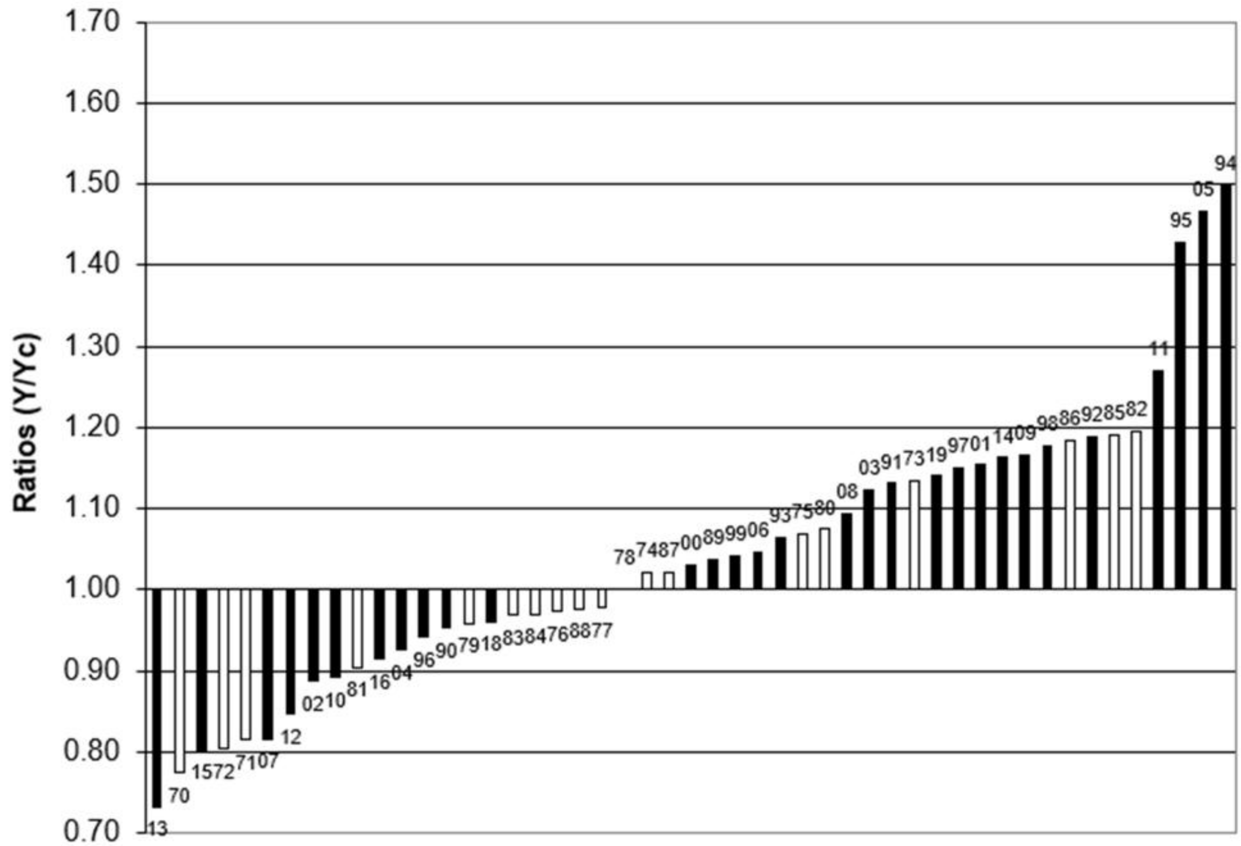


Figure 5.3 Calculated ratios for 1970-2019 December – March precipitation, Eastern Box Elder/Cache County Program, using the linear regression technique; White bars represent the historical, unseeded years and black bars the seeded years.

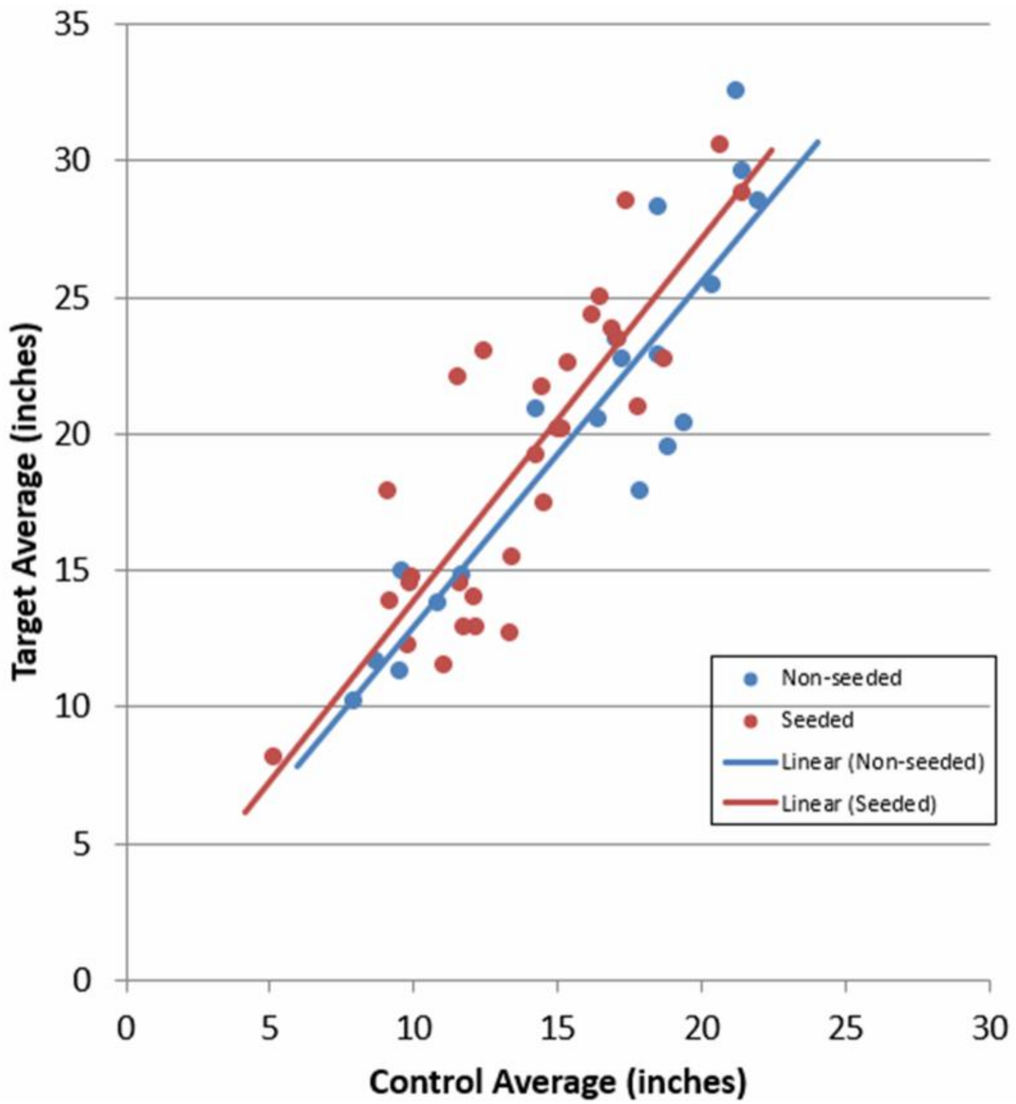


Figure 5.4 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for eastern Box Elder and Cache County precipitation linear regression

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 (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.

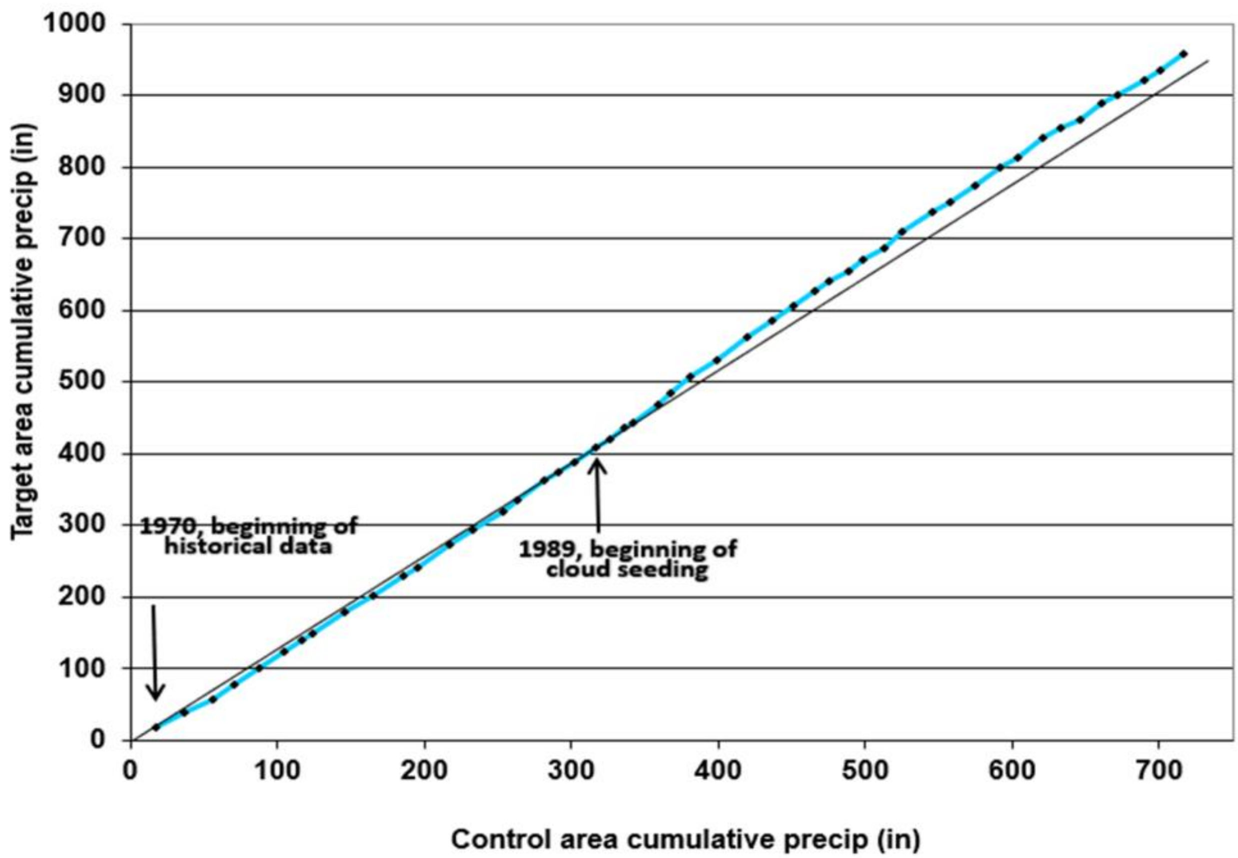


Figure 5.5 Double mass plot showing cumulative Dec-Mar <u>precipitation</u> for eastern Box Elder and Cache County target and control areas, water years 1970-2019.

5.3.1.5 Multiple Linear Regression Evaluation Results

The results of the multiple linear regression are similar to those for the linear regression. The resulting multiple linear regression ratio for this season is 1.15 with a ratio of 1.07 for the 30 seeded seasons of data, suggesting an average of 1.3 inches of increased water per season (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 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 snowcourse and SNOTEL snowpillow 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 snowpack 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 is the date on which the snowpack measurement was made. These measurements are generally made near the end of a month and, since the advent of SNOTEL, are made daily. However, prior to SNOTEL, and at those sites where snowcourses 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 snowcourse sites, but were converted to SNOTEL sites after approximately 1980. The data set that was utilized in some prior season evaluations contained both snowcourse and SNOTEL data for these sites. However, it was recognized that this could present a problem because of potential differences between the snowcourse and SNOTEL measurement techniques. The NRCS recognized this potential problem. Their solution was to obtain 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 correlations and mathematical relations between the two types of measurements. They then applied a correction factor at each site that converted the previous monthly snowcourse 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 snowcourse data while there were differences of 10-15% at a number of the sites. Our impression is that the SNOTEL observations had generally higher values than the snowcourse observations. After careful consideration, we decided that we should use these NRCS estimated data in place of the mixture of manual snowcourse and SNOTEL measurements as had been done in some prior years. We believe that using these NRCS estimates (rather than the previously used snowcourse data) can help eliminate, at least theoretically, any inherent systematic bias between data obtained using the snowcourse and SNOTEL measurement systems. The exception to this is one target site (Ben Lomond Trail), which does not have estimated SNOTEL data available for the pre-SNOTEL period and thus contains snowcourse data as before. Some sites today continue as manually observed snow course sites. The use of data from these sites continues without change. One of these sites (Klondike Narrows) was converted to a SNOTEL site in the 2009-2010 water year, and manual snowcourse observations ended in 2011. Thus, SNOTEL (instead of snowcourse) data are now being collected at that site.

5.3.2.1 <u>Target Area Snowpack Sites</u>

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 snowcourse sites. Figure 5.6 depicts these site locations as well, and Table 5-2 lists pertinent site data.

5.3.2.2 <u>Control Area Snowpack Sites</u>

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.

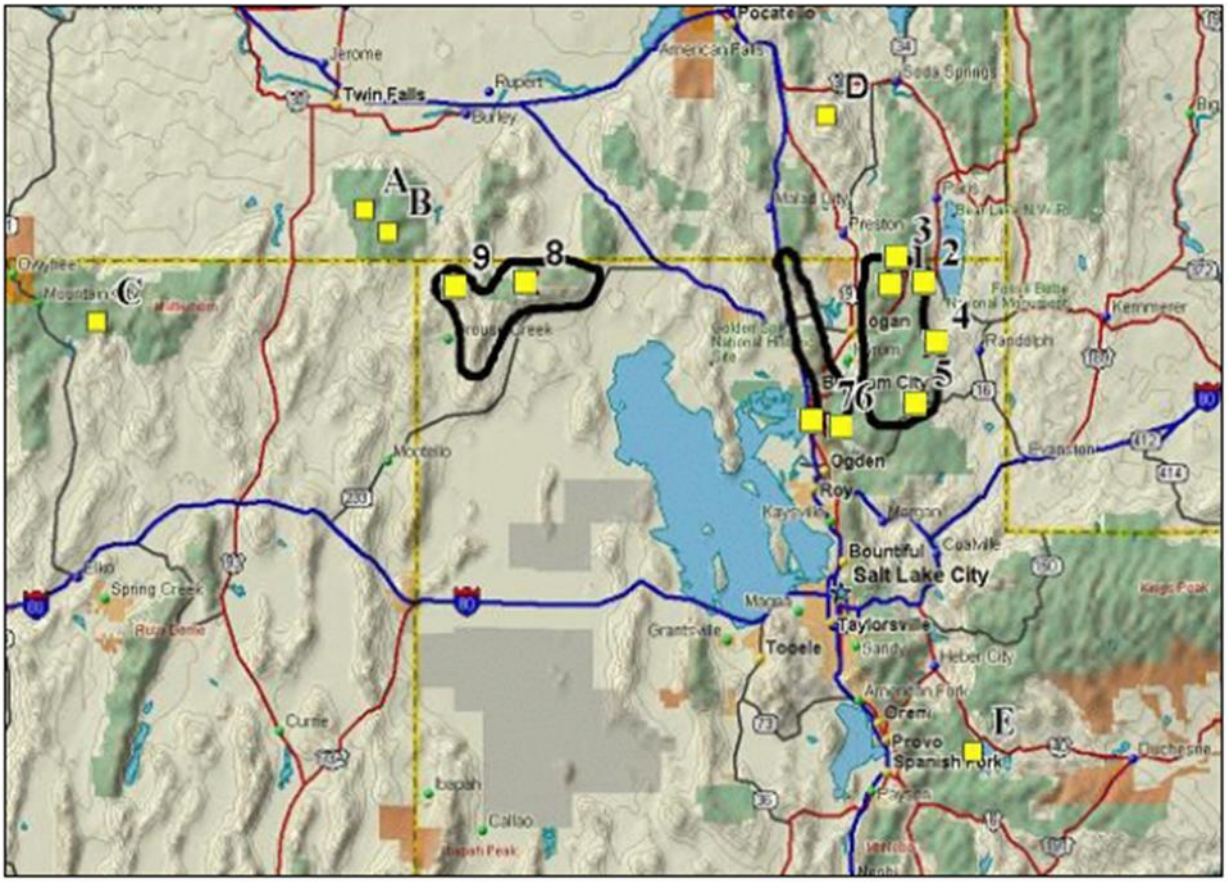


Figure 5.6 Target and control sites used in eastern Box Elder/Cache County snowpack evaluation, with site data shown in Table 4-2. The target areas are outlined in black. The target sites are numbered; the control sites have letter ID's.

Table 5-2

Snowpack Control and Target Measurement Sites

ID	Site Name	Site No.	Elev. (Ft)	Lat. (N)	Long. (W)
Control (for both areas)					
A	Magic Mountain, ID	14G02S	6,880	42b 11'	114b 18'
B	Badger Gulch, ID	14G03S	6,660	42b 06'	114b 11'
C	Big Bend, NV	15H04S	6,700	41b 46'	115b 41'
D	Sedgwick Peak, ID	11G30S	7,850	42b 32'	111b 58'
E	Strawberry Divide, UT	11J08S	8,400	40b 11'	111b 13'
Eastern Box Elder/Cache County Target					
1	Tony Grove Lake, UT	11H36	8,400	41° 54'	111° 38'
2	Garden City Summit, UT	11H07	7,600	41° 55'	111° 28'
3	Klondike Narrows, UT	11H01	7,400	41° 58'	111° 36'
4	Bug Lake, UT	11H37	7,950	41° 41'	111° 25'
5	Monte Cristo, UT	11H57	8,960	41° 28'	111° 30'
6	Ben Lomond Trail, UT	11H30	6,000	41° 23'	111° 55'
7	Ben Lomond Pk., UT	11H08	8,000	41° 23'	111° 57'
Northwestern Box Elder County Target					
8	George Creek, UT	13H05	8,840'	41°54'	113°29'
9	Vipont, UT	13H03	7,670'	41°54'	113°51'

5.3.2.3 Regression Equation Development

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

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

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

For northwestern Box Elder County, the equation is:

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

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

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

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

where $X_1....X_5$ 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 is reduced from five to two. Grouping is typically done based on geography, with sites in a given area typically sharing similar meteorological characteristics. 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

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

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:

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

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

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

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, 2019 snow water content averaged 19.30 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 29.27 inches. The measured average target area water content was also 28.19 inches, which yields an observed/predicted ratio of 0.96 for the eastern Box Elder/Cache County portion of the target**.** The average increase for the 30 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 1.6 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).

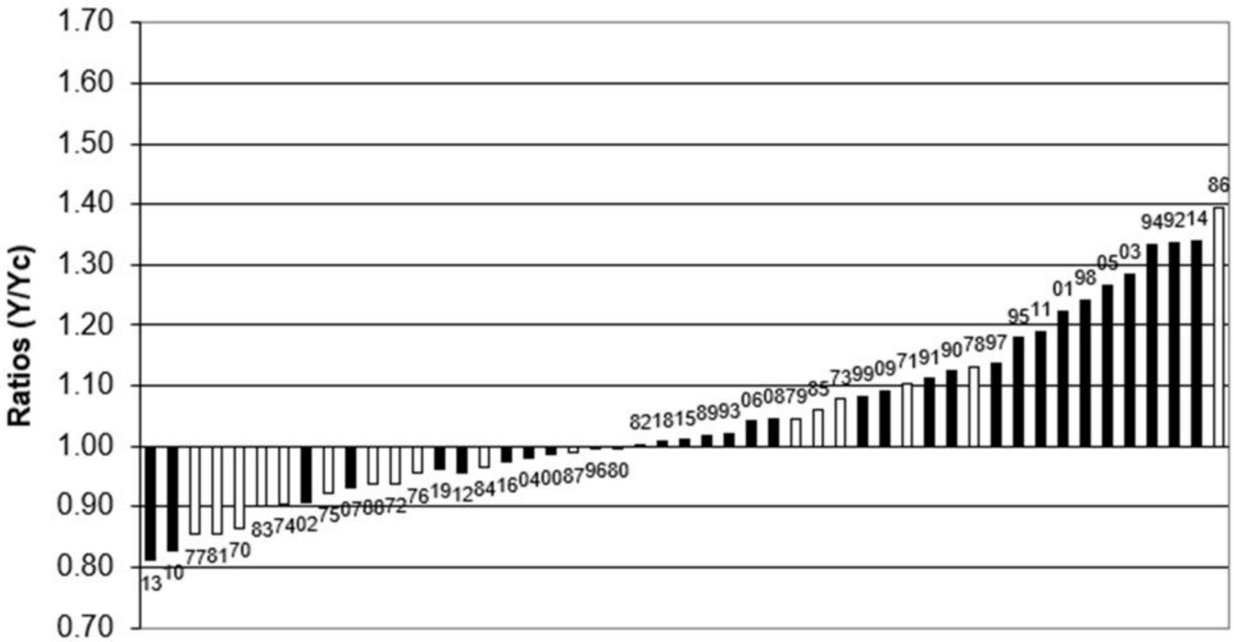


Figure 5.7 Calculated ratios for 1970-2019 April 1st snow water content, using the linear regression technique, <u>Eastern Box Elder/Cache Counties</u>. White bars = historical (unseeded) seasons; black bars = seeded seasons

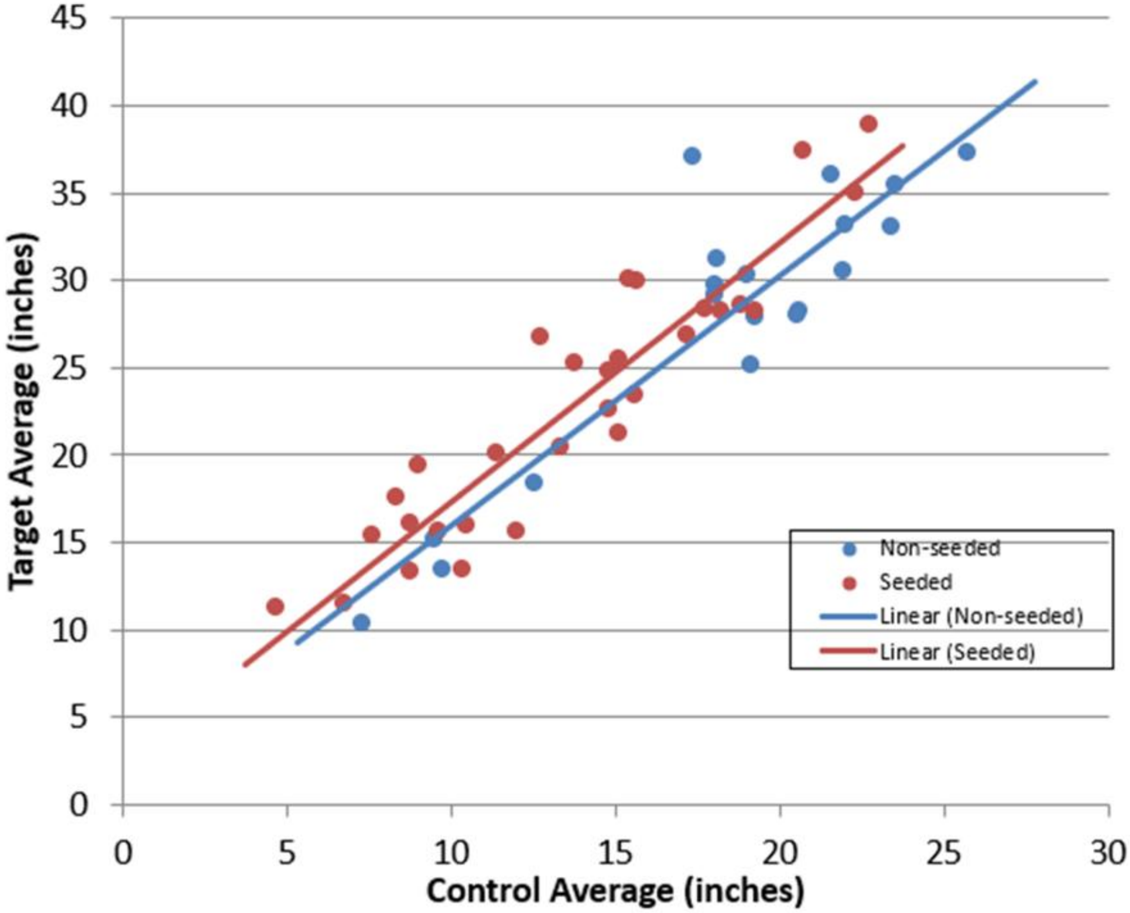


Figure 5.8 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for eastern Box Elder and Cache County snowpack linear regression.

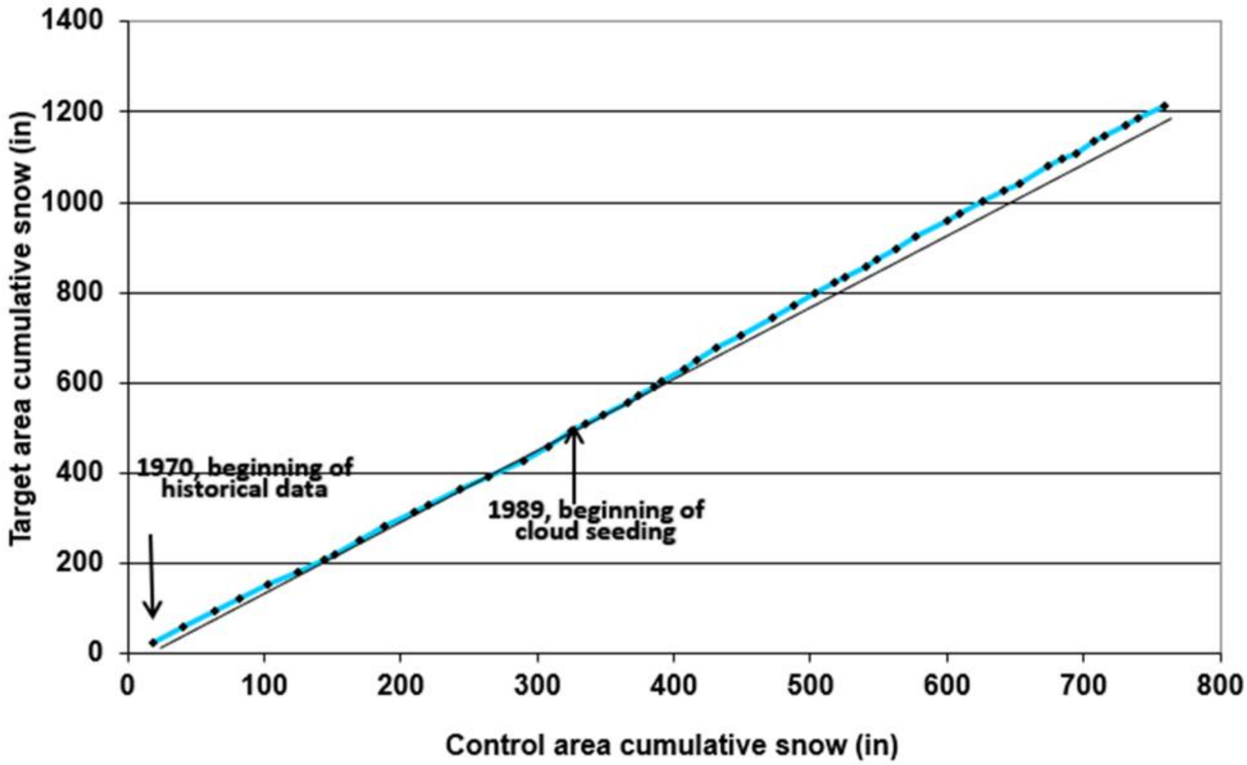


Figure 5.9 Double mass plot showing cumulative April 1 snow water content amounts for eastern Box Elder and Cache County target and control areas, water years 1970-2019.

In the northwestern Box Elder County portion of the target, the April 1, 2019 observed water content was 22.70 inches, with a predicted value of 20.45 inches. This yields an observed/predicted ratio of 1.11 for the northwestern Box Elder County portion of the target for this season. The average increase for the 26 seeded seasons (through 2019) is 13 percent, and the average estimated increase in snow water content is 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.

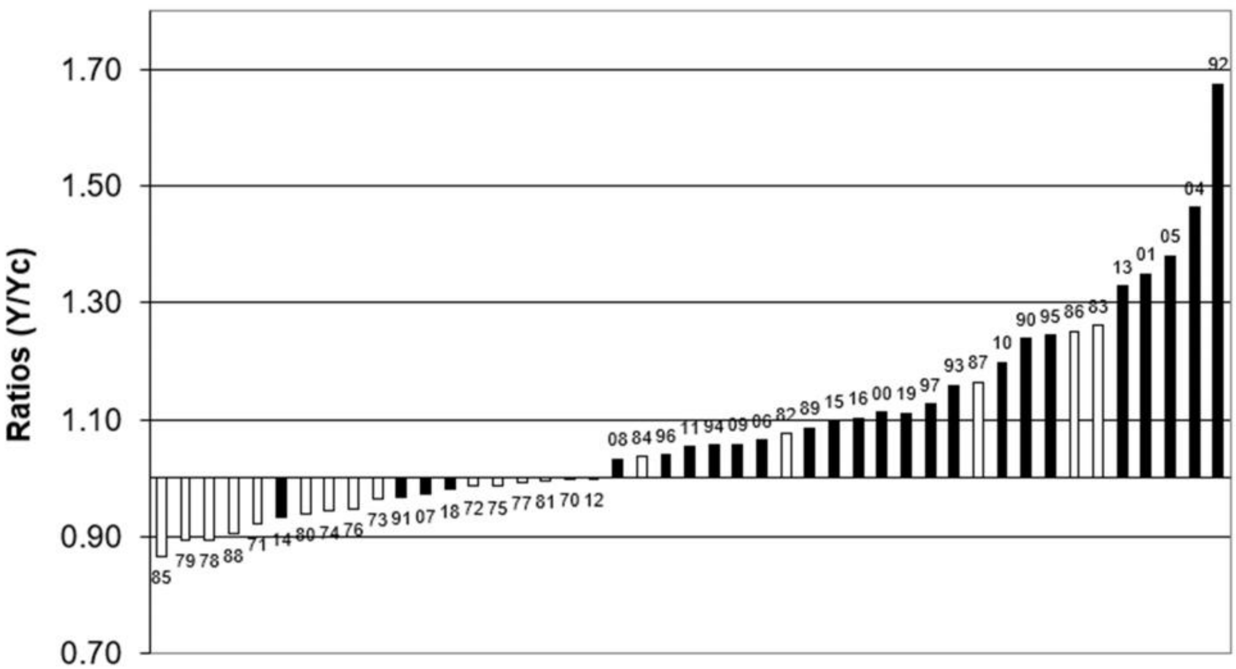


Figure 5.10 Calculated ratios for 1970-2019 April 1st snow water content, using the linear regression technique, Northwest Box Elder County. White bars are historical (unseeded) seasons; black bars = seeded seasons; 1998, 1999, 2002, 2003, and 2 are not shown because of no seeding in those years. 2017 was also excluded.

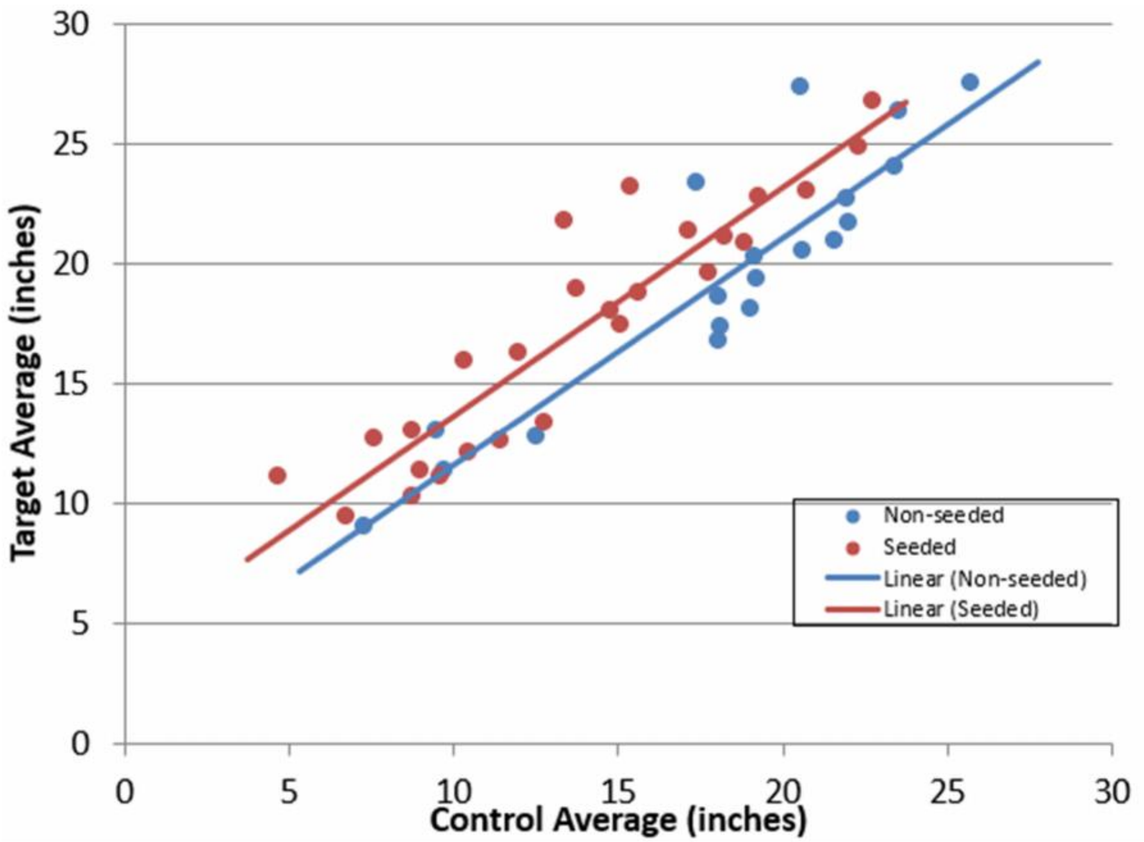


Figure 5.11 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for Northwest Box Elder County snowpack linear regression

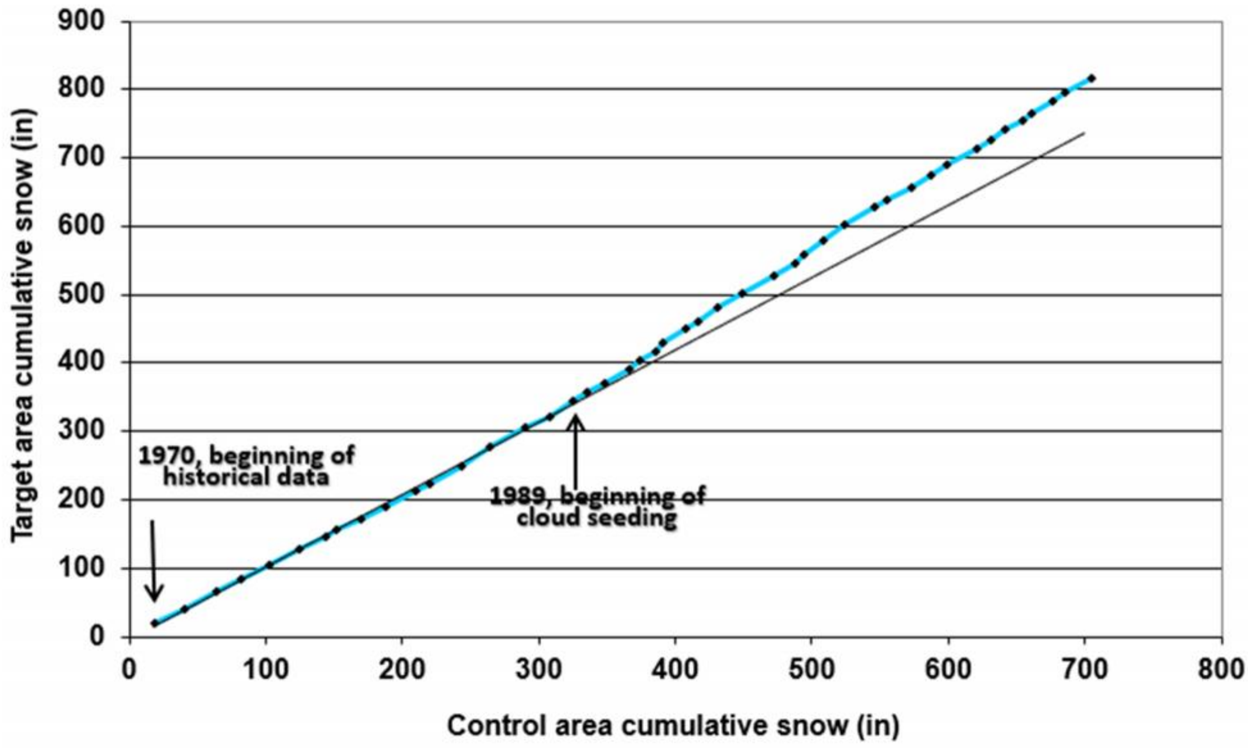


Figure 5.12 Double mass plot showing cumulative April 1 snow water content amounts for Northwest Box Elder County target and control areas for water years 1970-2019 (plot excludes the water years 1998, 1999, 2002, and 2003, when no seeding was conducted, as well as water year 2017).

5.3.2.5 Results of Multiple Linear Regression Snowpack Evaluation

The multiple regression evaluation resulted in ratios of 0.92 and 1.01 this season for the Eastern Box Elder/Cache County area and the Northwestern Box Elder County area, respectively. The long-term indications (through 2019) 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 30 seasons of seeding. These results are similar to the linear regression equations results. For northwestern Box Elder County, the long-term analysis shows a 10% increase (about 1.6 inches of additional snow water) based on the multiple linear equation for 26 seasons of seeding. These and other evaluation results are shown in detail in Appendix B.

5.4 <u>Discussion of Evaluation Results</u>

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

This year's evaluation results for the eastern Box Elder and Cache County portion of the target area (December – March precipitation, and April 1 snowpack), and for Northwestern Box Elder County (April 1 snowpack) were quite 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 30 seeded seasons in the Eastern Box Elder/Cache County portion of the target indicate 7-12% increases in April 1 snowpack (an average of 1.7-2.5 inches of excess water) and a 6-7% increase in December through March precipitation (1.1" of additional water). These cumulative results likely constitute a reasonable estimate 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, 2018-2019 and all Seeded Seasons.

Area	Ratio Observed/Predicted		Excess Water inches	
	Linear	Multiple Linear	Linear	Multiple Linear
Cache/E. Box Elder Dec-Mar Precip.	2019: 1.14 **30 yrs: 1.06**	2019: 1.15 **30 yrs: 1.07**	2019: +2.7 **30 yrs: +1.1**	2019: +3.0 **30 yrs: +1.3**
Cache/E. Box Elder April 1 Snowpack	2019: 0.96 **30 yrs: 1.07**	2019: 0.92 **30 yrs: 1.12**	2019: -1.1 **30 yrs: +1.6**	2019: -2.5 **30 yrs: +2.5**
NW Box Elder April 1 Snowpack	2019: 1.11 **26 yrs: 1.13**	2019: 1.01 **26 yrs: 1.10**	2019: +2.2 **26 yrs: +2.0**	2019: +0.2 **26 yrs: +1.6**

Snowpack evaluations for the Northwestern Box Elder County portion of the target area this season produced single season observed/predicted ratios of 1.11 (linear regression) and 1.01 (multiple linear). The long-term results indicate average increases for the 26 seeded seasons of +13% (linear) and +10% (multiple linear), which is equivalent to about 1.6 – 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 B 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 2018-2019 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, 2018 through March 31, 2019 for portions of Box Elder and Cache Counties. During the season, there were 17 seeding operations conducted on portions of 29 days. Five storms were seeded in December, three in January, three in February, and six in March. A cumulative 2,051.75 hours of operations were conducted from all the generator sites during the season.

Precipitation was above normal in northern Utah during the 2018-2019 winter season. Snowpack in the Bear River Basin on April 1, 2019 averaged 115% of normal (median), with about 108% 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 2018-2019 winter season, for the Eastern Box Elder/Cache County portions of the target, show observed-to-predicted ratios of 1.14 and 0.96 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 30-season seeded period through 2019. 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 2018-2019 linear snowpack evaluation resulted in an observed/predicted ratio of 1.11. **The average increase in April 1st snow water content in northwest Box Elder County is 13% for the 26 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 that can be used 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.

Table 6-1
Comparison of Results of Linear and Multiple Linear Analyses, 2018-2019 and all Seeded Seasons.

Area	Ratio Observed/Predicted		Excess Water inches	
	Linear	Multiple Linear	Linear	Multiple Linear
Cache/E. Box Elder Dec-Mar Precip.	2019: 1.14 **30 yrs: 1.06**	2019: 1.15 **30 yrs: 1.07**	2019: +2.7 **30 yrs: +1.1**	2019: +3.0 **30 yrs: +1.3**
Cache/E. Box Elder April 1 Snowpack	2019: 0.96 **30 yrs: 1.07**	2019: 0.92 **30 yrs: 1.12**	2019: -1.1 **30 yrs: +1.6**	2019: -2.5 **30 yrs: +2.5**
NW Box Elder April 1 Snowpack	2019: 1.11 **26 yrs: 1.13**	2019: 1.01 **26 yrs: 1.10**	2019: +2.2 **26 yrs: +2.0**	2019: +0.2 **26 yrs: +1.6**

NAWC produced various plots for the precipitation and snowpack analyses (described and shown in Section 5.4), which provide a visual indication 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 from this recent report for the various seeding target areas in Utah are summarized in Table 6-2.

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 assessment 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 via well-considered and carefully administered policies and strategies.

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 representative SNOTEL sites, has been developed as a guide for potential suspension of operations.

a. 200 % of average on January 1

b. 180 % of average on February 1

c. 160 % of average on March 1

d. 150 % of average on April 1

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. Only the Bear River division applies to the Northern Utah project. 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.

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 or increasing 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 relevant in the conduct of winter cloud seeding programs include the following:

- **Snow Advisory** - This product is issued by the NWS when four to twelve inches of snow in 12 hours, or six to eighteen inches in 24 hours, are forecast to accumulate in mountainous regions above 7000 feet. Lower threshold criteria (in terms of the number of inches of snow) are issued for valleys and mountain valleys below 7000 feet.

- **Heavy Snow Warning** - This is issued by the NWS when it expects snow accumulations of twelve inches or more per 12-hour period or eighteen inches or more per 24-hour period in mountainous areas above 7000 feet. Lower criteria are used for valleys and mountain valleys below 7000 feet.

- **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 Warnings** - 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 Heavy Snow or 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). In these cases, 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

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
Mean	13.82	18.98	17.85	**1.06**	**1.13**

* 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**

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
Mean	19.85	12.46	14.89	8.09	18.98	17.72	**1.07**	**1.26**

* 2017 not included in mean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.93659
R Square	0.87719
Adjusted R Square	0.8421
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
2004	13.38	20.41	20.68	0.99	-0.27

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
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
Mean	13.72	22.85	21.29	**1.07**	**1.56**

* 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
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

YEAR	Magic Mtn Pil	Badger Gulch Sc	Big Bend Pil	Sedgewick Pk Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
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
Mean	17.39	11.36	6.12	19.02	14.72	22.85	20.35	**1.12**	**2.50**

* 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	2.4375 8	-2.1513	0.0508	-10.51	0.022	-10.51	0.0220 3	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
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
Mean	13.76	17.18	15.19	**1.13**	**1.99**

* 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
Mean	17.4	11.4	19.1	6.0	14.9	17.2	15.6	**1.10**	**1.57**

* 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
Adjusted R Square	0.833215
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

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