CLOUD SEEDING ANNUAL REPORT

Prepared for

Range Valley Ranch

by

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The Science Behind Cloud Seeding

The Science

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

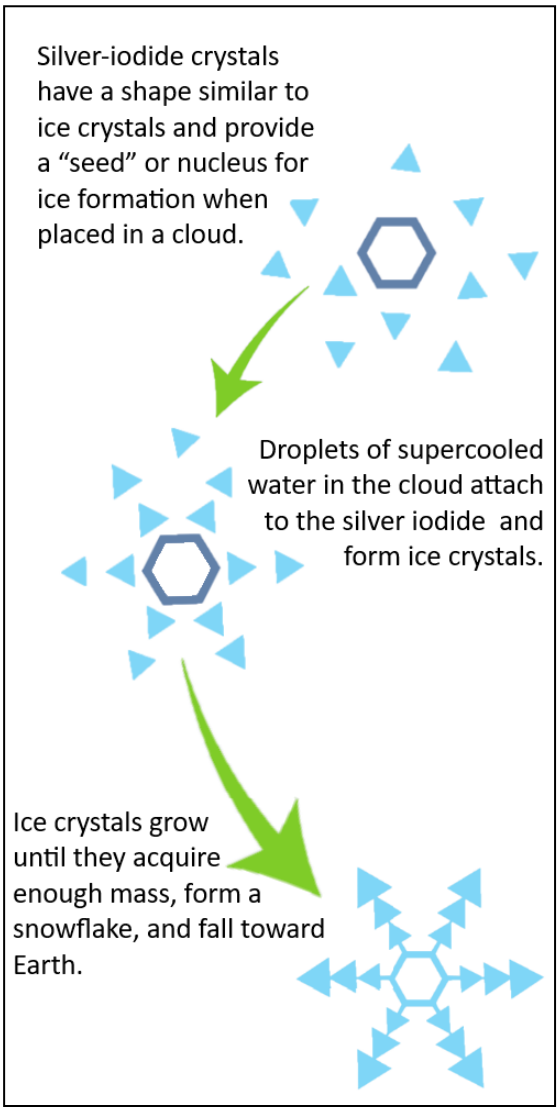
Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.

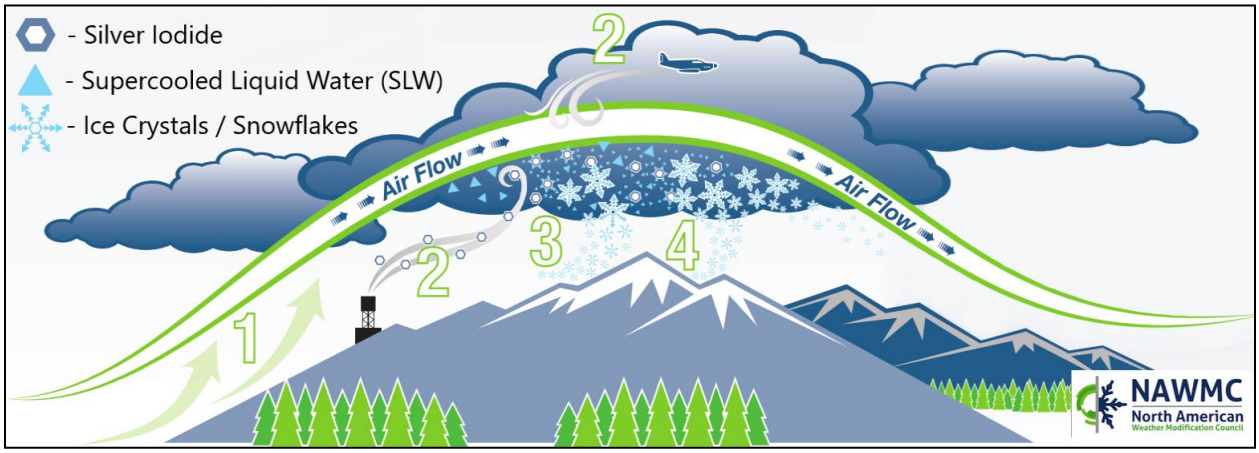
Safety

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

Effectiveness

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





STATE OF THE CLIMATE

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

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

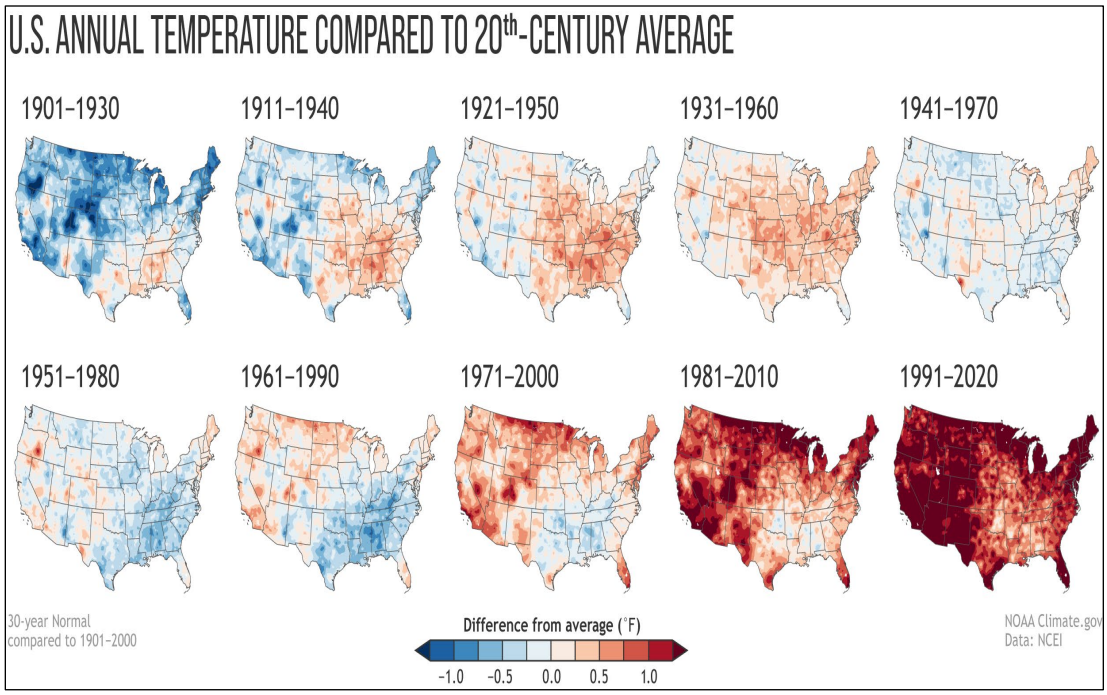


Figure 1 U.S. Annual Temperature compared to 20th-Century Average

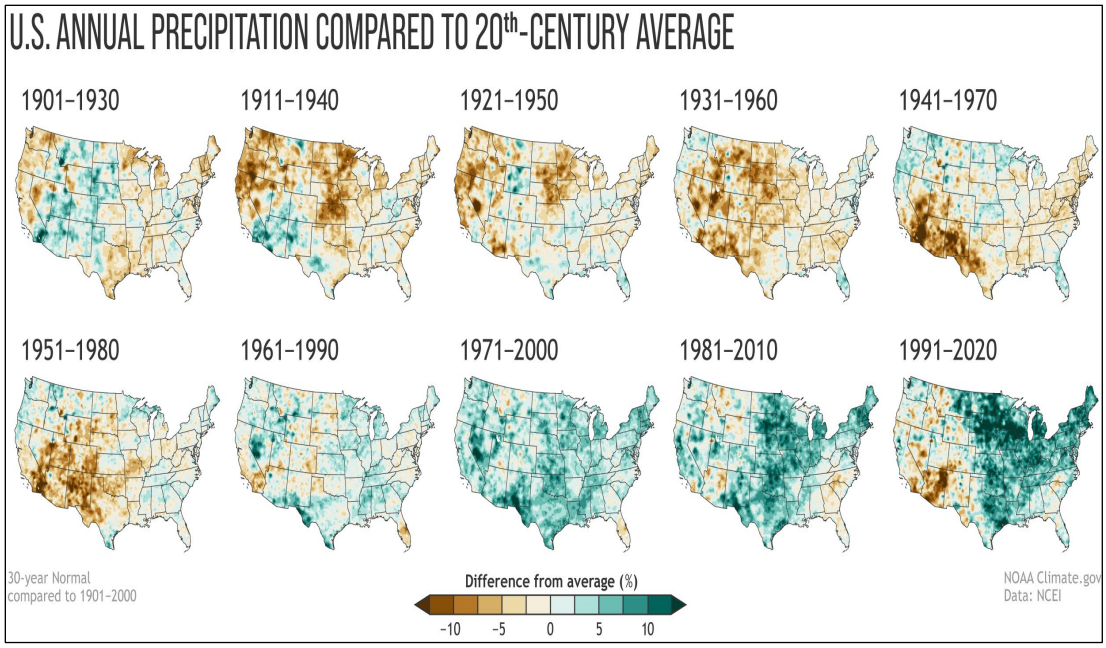


Figure 2 U.S. Annual Precipitation compared to 20th-Century Average

1.0 BACKGROUND

North American Weather Consultants (NAWC) has been involved in cloud seeding operations since the 1950s, beginning in California and in more recent decades, various other states and countries. Due to high natural precipitation variability and the increased demand for water, cloud seeding has been conducted over large areas of Utah for over 40 years. Cloud seeding in Utah is regulated and cost shared by the Utah Department of Natural Resources through the Division of Water Resources.

Most cloud seeding programs in Utah are conducted for relatively high-yield areas of the Wasatch Range and Plateau, areas from the northern to southern borders of the state, as well as the Uinta Range in northeastern Utah. These programs are normally conducted from November to April in order to target winter storms.

In 2020, NAWC was contacted by Daniel Campbell from the Range Valley Ranch requesting information regarding the potential for cloud seeding operations over the Tavaputs Plateau with the intent of increasing winter season precipitation. Upon further discussion, it was determined that there were multiple entities with a vested interest in augmenting the precipitation that occurs in portions of the Rocky Mountains around the Tavaputs Plateau. In order to determine the feasibility of a program in this area of Utah, NAWC performed preliminary research to estimate the potential increase in precipitation and runoff in the area.

Due to the remote nature of this portion of the Rocky Mountains, snow gauges and stream flow gauges are limited, as are historic records. Fortunately, NAWC's experience in other portions of the state, particularly those portions of the state with similar geographical and climatological patterns, assisted in the development of increase estimates for the the area covered by this program. For reference, NAWC's assessment of seeding potential in the Book Cliff's Range has been included in this report as sections 1.1 through 1.4.

1.1 Seasonal Precipitation

To determine the potential efficacy of a program and the value of such a program, NAWC first evaluates historical precipitation data for the intended target area. Two measures are of particular importance when determining the value of a cloud seeding program. The first is the total precipitation that occurs during portions of the calendar year when storms are typically seeable. This is typically measured in inches of total precipitation. The second, which is only applicable to higher elevation cloud seeding programs, is a measure of the amount of water stored in snowpack throughout the cold season. This is measured in terms of snow water equivalent (SWE).

To determine the values for these key metrics, NAWC utilizes data from Snow Telemetry (SNOTEL) sites, administered by the United States Department of Agriculture (USDA). Higher areas of the Tavaputs Plateau (east of Price) have two available SNOTEL

sites: the Timberline site at 8,736 feet elevation (established during the 2007-08 season) and Corral site at 8,207 feet (established during the 2013-14 season). These two sites, as well as another site near the western edge of the target area (Indian Canyon) at the summit along Highway 191, are designated in Figure 1 as blue circles. The Indian Canyon site is over 9,000 feet in elevation and does have a long term record, although is less representative of the core area of this seeding program.

Although the Timberline and Corral sites are too new to have a sufficient period of record for a reliable long-term normal value, the available record suggests that SWE values peak in March with median values near 8 inches of liquid water equivalence at Timberline and near 6 inches at Corral. Snowfall in these areas tends to be highly variable with dry years receiving as little as half the median precipitation and the wettest years receiving nearly double the median precipitation amounts.

Annual precipitation in this area, exhibits an overall maximum from late July to early/mid-October, associated with a seasonal monsoonal pattern. The driest months tend to be during late fall to early winter (November/December), with the November - April season representing roughly half (or slightly less) of the annual total precipitation of 20-25 inches on average.

1.2 Climate Overview

Climate analysis for the Book Cliffs / western Tavaputs Plateau area was conducted by NAWC based on two SNOTEL sites (Timberline and Corral) located near the center of the target area. The analyses showed that the winter climate is somewhat drier in this area than that of most areas with winter seeding programs. These sites receive roughly 8-10 inches of precipitation / snow water content during the November – April period on average, although there is a high year to year variability. In some wet years, these sites can receive as much as 15-20 inches during the winter season period, and in dry years can receive less than 6 inches. A large portion of precipitation that falls in these areas occurs during the summer monsoon period from roughly late July to early October. This warm season precipitation is not considered seedable from ground-based sites due to temperature parameters, as well as its minor contribution to runoff and water storage. Seeding during the winter season can add additional moisture to the snowpack which contributes substantially to runoff and water storage. One key attribute of the eastern Utah basins and mountains is that the highest producing winter season precipitation periods are associated with south to southwesterly winds, with westerly to northerly wind patterns generally associated with drier conditions. These and other attributes have impacted the program design that was recommended and implemented for the Book Cliffs program.

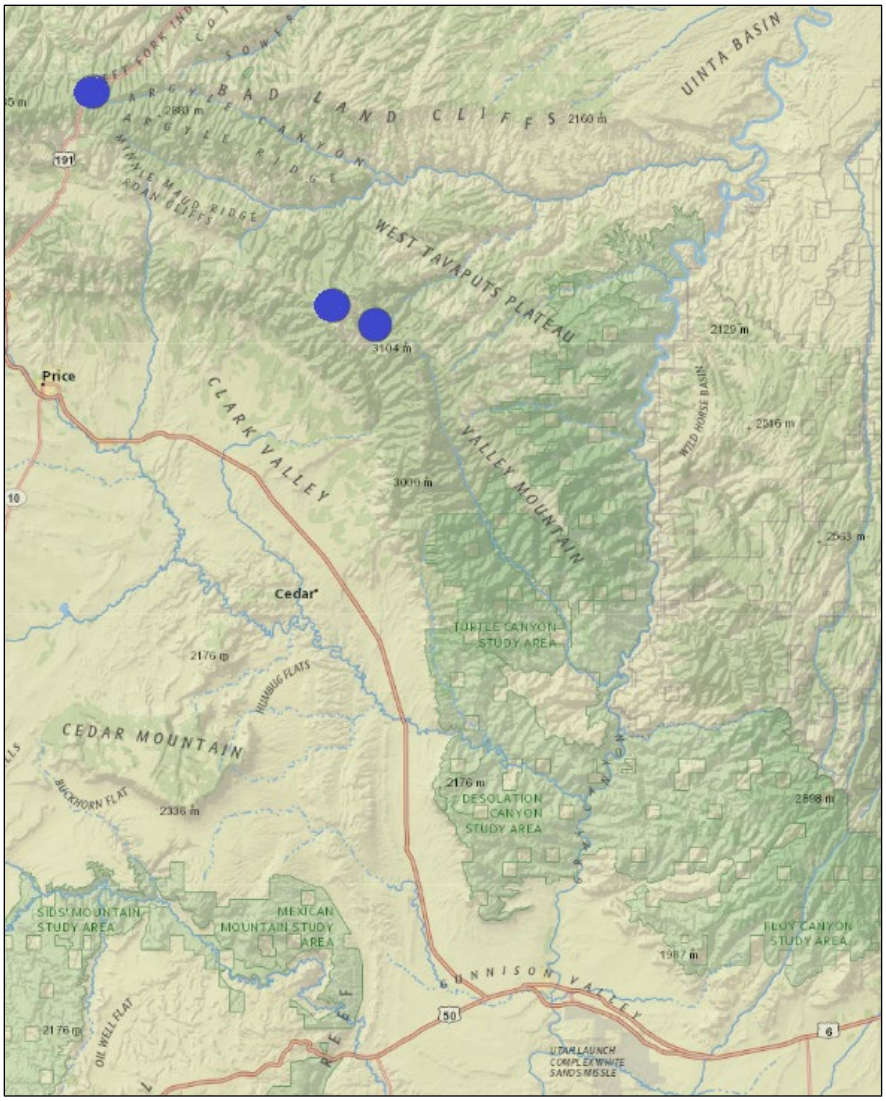


Figure 1. Location of SNOTEL sites in the Book Cliffs area.

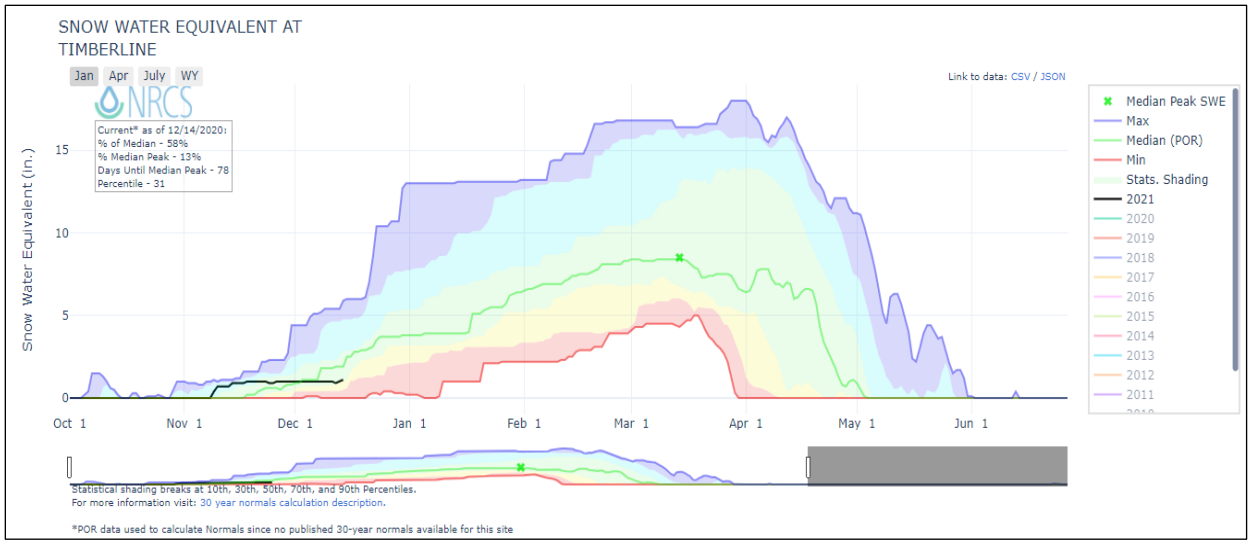


Figure 2. Snow water equivalent values at the Timberline SNOTEL site

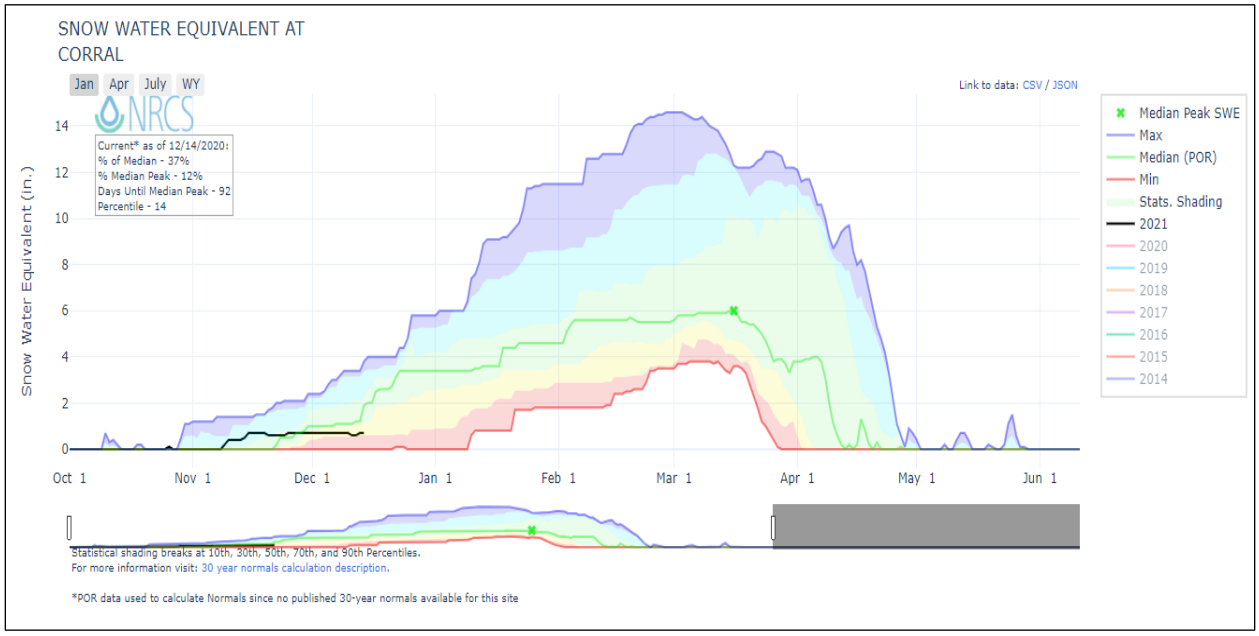


Figure 3. Snow water equivalent values at the Corral SNOTEL site

There are two potential concerns with targeting this area with cloud seeding operations. The first, is that winter storms (or portions of storm) that come from the south do tend to be somewhat warmer than precipitation periods with northwesterly winds. Cloud seeding agents are generally most active at temperatures between -5° and -15° C. Due to the warmer nature of these southerly storms, the -5° C level inside the cloud deck may be found at elevations higher than the mountain barrier. This is often the case with NAWC's California programs, and it does not always negate cloud seeding efforts but can render a program less effective. The second concern is that low-level thermodynamic stability (inversion) can affect the dispersion of seeding material from ground-based sites.

Though the prevalence of stability is not as notorious in this region as it is in the Uinta Basin, this is something operational meteorologists will be aware of in regards to program design and seeding increase projections.

1.3 Pre-Season Increase Projections

Based on all of the considerations, it was estimated that this area could be reasonably targeted by an array of four or more ground-based sites, ideally located above the valley floor (above the 6,000-foot elevation level) to maximize material dispersion.

Long term historic records and extensive mathematical modeling using these records have produced seasonal seeding increase estimates of 3 to 15% in precipitation for well executed weather modification programs, in the Utah and Colorado Rockies. The program most topographically and climatologically similar to this proposed program is the weather modification program comprising the eastern two thirds of the Uinta Mountain Range. Data for the Uintas program suggests an increase in seasonal precipitation that is on the lower end of the overall range shown above, or roughly 3-5% resulting from cloud seeding endeavors. We therefore predict an estimated seasonal increase of a similar 3-5% for the November – April period for the Book Cliffs program given its climatological and topographical similarities. **This would equate to roughly 0.3 to 0.5 inches of additional precipitation (liquid water equivalent) or roughly 3-5 inches of additional seasonal snowfall. Based on the size of the target area (outlined in Figure 4), NAWC expects that this increase would amount to between 10,000 and 20,000 acre-feet (AF) of additional snowmelt runoff**, depending on the nature of seasonal weather patterns.

1.4 Post-Season Assessment

As only a single season of seeded data is available in the Book Cliffs, data derived from the Uinta Range seeding programs were used to estimate precipitation increases for the Book Cliff seeding program, as was discussed in the feasibility report. Based on this year's precipitation totals during the program (roughly mid-January through the end of April) of about 7.5 inches, it is estimated that an increase of 0.3 inches resulted from cloud seeding efforts in the target area. Though the target area encompasses almost 700,000 acres, for the purpose of estimating precipitation increases, we are only considering the 500,000-acre portion of the target area with the best coverage from the current ground generator network. Applying the 0.3" increase to this portion of the target area **results in an estimated increase in seasonal precipitation of 12,500 acre-feet.**

1.5 Program Design

In order to maximize the program coverage and contribution to spring runoff, operational seeding sites were distributed north, from the Helper area, south east to Green River, with the primary target area being those areas of the Tavaputs Range that exceed 6,000 to 7,000 ft in elevation. Desirable generator locations as well as NAWC's proposed

target area are represented in Figure 4. It should be noted that, unfortunately, the Nine Mile Canyon site was eliminated during the season due to land use considerations.

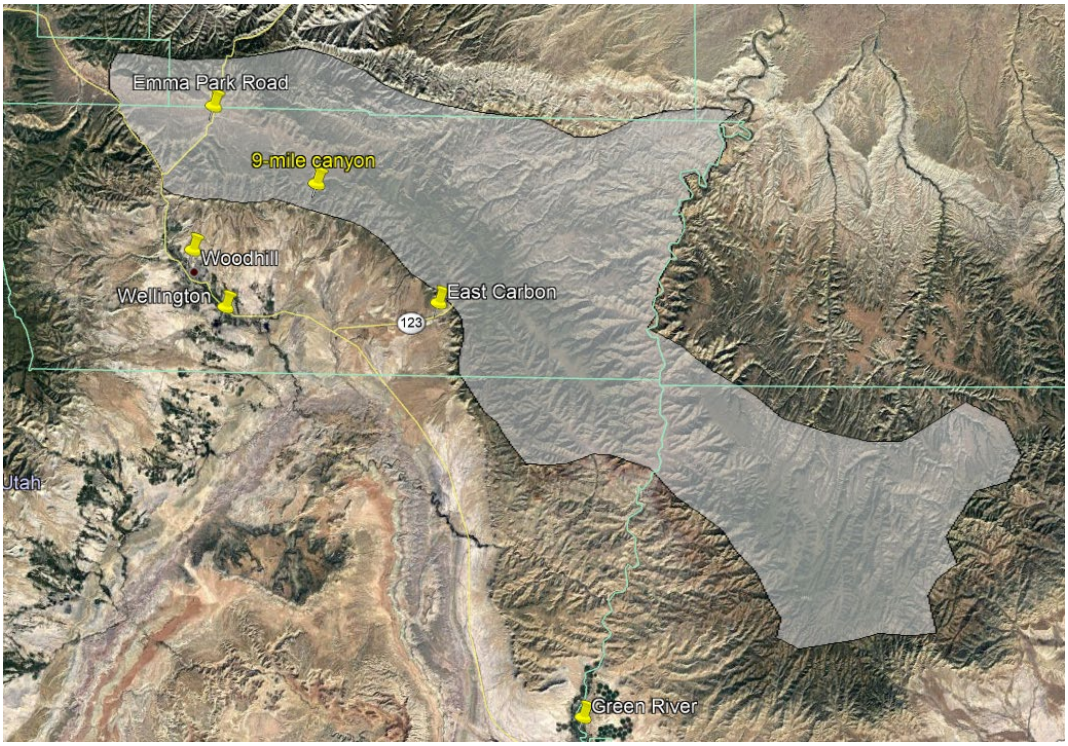


Figure 4. Book Cliffs seeding sites and target area

Estimates of potential cloud seeding benefits in the Book Cliffs area were based on those made for seeding in the Uinta Range, given the general proximity and similarities of climate and barrier orientation. While many winter programs in Utah are estimated to produce increases of 5-10% or locally more to the winter snowpack, estimates for the Uinta Range are lower, on the order of 3-5% and these estimates were used as the basis for the Book Cliffs program. A 4% increase, applied to total winter season precipitation in the Book Cliffs, results in an estimate of roughly a 0.4 inch potential increase for seeding in the Book Cliffs.

This report summarizes operations conducted for the Book Cliffs program during the January - April 2021 season, as well as development of target/control precipitation and snowpack equations, which could become useful for the estimation of seeding benefits if the program continues.

2.0 OPERATIONS DURING THE 2021 SEASON

The 2021 season was below normal region wide in terms of storm activity and snowpack. Snow water equivalent (SWE) peaked around April 1 in higher portions of the Book Cliffs seeding target area, where two of the previously mentioned SNOTEL sites are located. SWE values of around 6 to 8 inches were observed on April 1, which is somewhat below the average for the (short) existing periods of record at these sites. In general, the snowpack here, similar to much of the state, appeared to peak at around 70 – 80 % of the average values this season.

Figure 5 is a graph of snow water equivalent (SWE) and cumulative water year precipitation, which begins October 1, for the Timberline SNOTEL site in the target area. Figure 6 is a similar plot for the nearby Corral SNOTEL site. Normal values for these sites have not yet been officially established due to the short period of record, and so are not shown in the graphs. As seen in these graphs, snowpack quickly melted at these sites during a period of warm weather in early April. Water year precipitation to date (as of May 1) ranged between 10 – 12 inches at these sites.

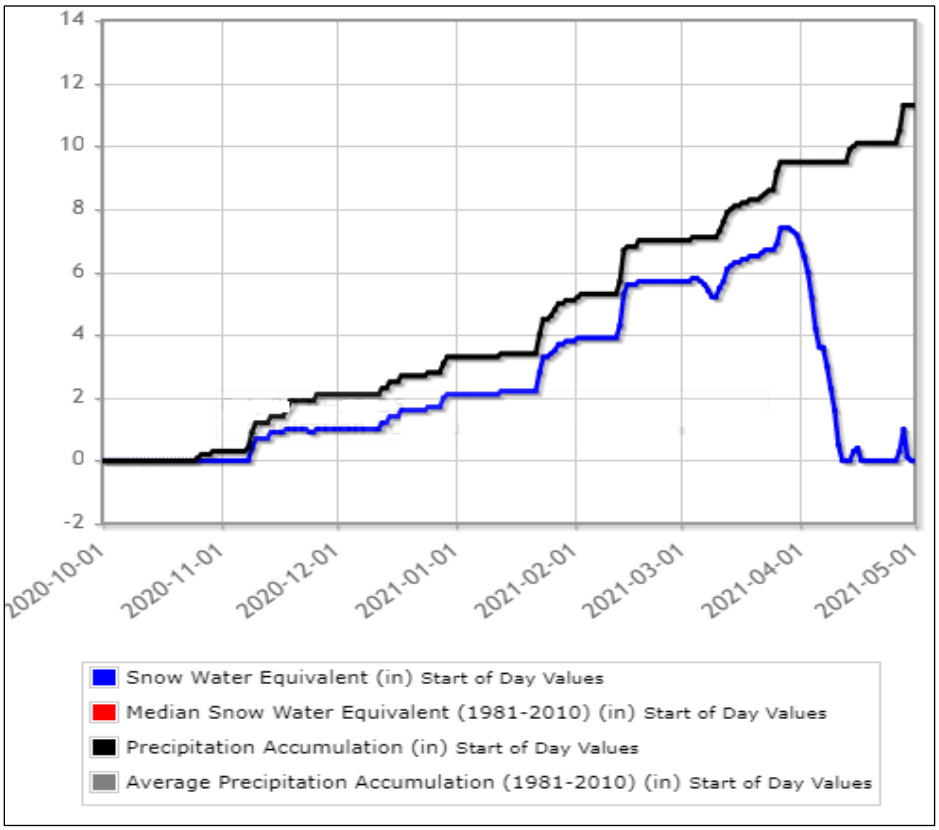


Figure 5. SNOTEL graph for Timberline site

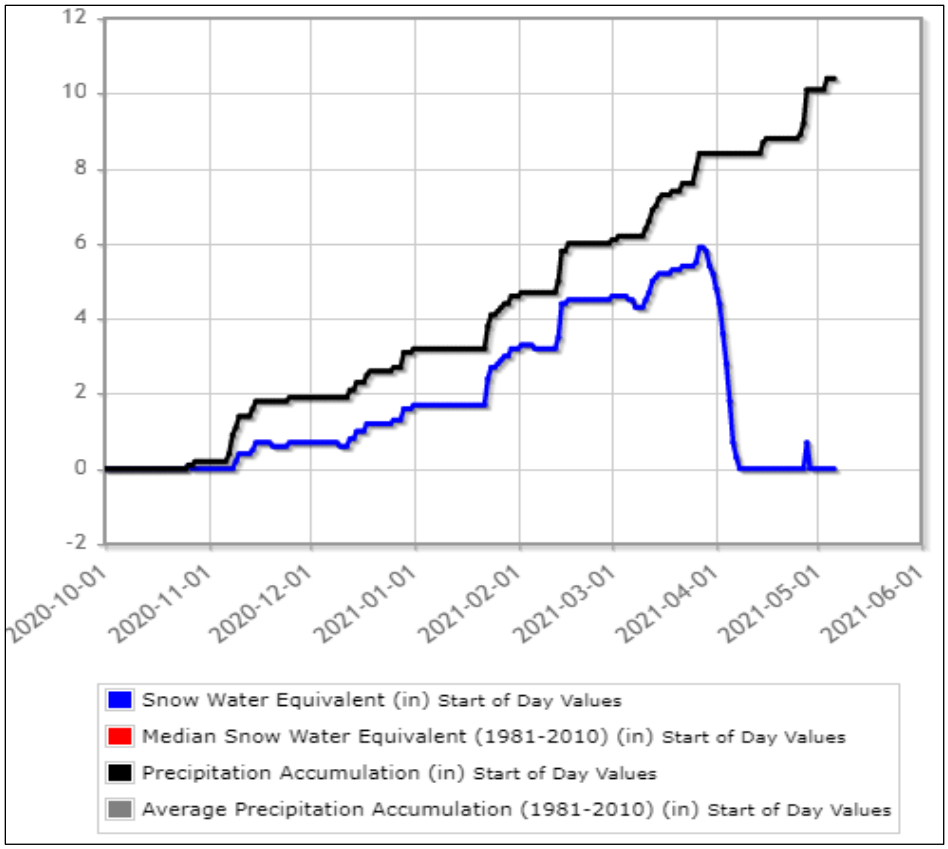


Figure 6 SNOTEL graph for Corral site

A total of eight seeded storm events occurred for the Book Cliffs program during the period of January through April 2021. Seeding activity during each of these events is shown in Table 1. A total of 350.5 generator hours were utilized during the season.

Table 1

Summary of seeding operations during the season

Storm #	1	2	3	4	5	6	7	8
Site	**Jan 22-23**	**Jan 29**	**Feb 13-14**	**Feb 15-16**	**Mar 11**	**Mar 25-26**	**Apr 14**	**Apr 26-27**
Emma Park			18.75		9.75			
Wood Hill		5.25	19.25	13.5	9.75		7.5	
9 Mile Canyon*			22.25		27.5			
Wellington			8.25	14.25	10	12.25	7.5	20
East Carbon	17.5	5.25	8.25	14.75	11	18.75	7.25	20
Green River	17.5		7.5					17
Event Total	35	10.5	84.25	42.5	68	31	22.25	57

* The 9 Mile Canyon site was decommissioned in March due to a land use decision by the county

2.1 Storm Summary

The first seeded event of the season took place on January 22-23, as moisture was advected northward from Arizona into Utah ahead of a low pressure trough moving into the Great Basin. Some convective shower activity began in a southerly wind pattern in the afternoon, with a 700 mb temperature near -5° C. This appeared favorable for seeding operations, which began from a couple of sites (East Carbon and Green River) in the mid to late afternoon. Shower activity and seeding continued overnight, ending early on January 23rd. Precipitation totals ranged up to nearly an inch of water in higher portions of the area with this system.

A trough moved eastward from California into Nevada/Utah late on January 29, providing another seeding opportunity. Seeding began late afternoon at the Woodhill and East Carbon sites as light precipitation began. Temperatures cooled to below -5° C during the evening hours with arrival of the trough. Winds shifted to a northwesterly direction overnight which was not favorable for seeding the Book Cliffs program, so seeding operations were terminated late in the evening. Precipitation with this system was brief and light, with only around 0.1 inches of water equivalent.

A significant storm event beginning on February 13th brought widespread rain and snow to the area, with a 700 mb temperature near -6° C. As the trough axis moved across Utah overnight, with precipitation tapering off and winds shifting to the north during the night. However, seeding operations continued at a few sites during that night which appeared somewhat favorable. Observed precipitation totals were generally near an inch or more at the Timberline and Corral SNOTEL sites from this event, and all of the seeding sites were utilized.

Seeding was conducted during the evening to overnight February 15-16 as a moist northwesterly flow pattern was over the area. The 700-mb temperature warmed somewhat from about -12° to -10° C during the day. While the majority of the precipitation occurred in mountain ranges upstream of the Book Cliffs target area, precipitation amounts of 0.1–0.2 inches were observed. Seeding operations ended early on the 16th.

A closed low centered over California and Nevada on March 11 brought periods of precipitation to Utah in southwesterly flow with a 700 mb temperature near -8° C. Seeding began early and continued through the afternoon hours, before lower level winds became variable or shifted to light northerly and seeding operations ended. Seeding was conducted from all sites except Green River, due to unfavorable wind patterns there. Observed precipitation totals were near a half inch of SWE.

A large trough of low pressure moved from the Pacific Northwest into the Great Basin on March 25. Clouds over Utah were very high initially with an ice-dominated precipitation process beginning later in the day. Seeding began later in the evening, however, with anticipation of improving conditions overnight. The 700 mb temperature was near -6° C cooling to around -8° C overnight. Winds remained generally light southwesterly overnight but become northwesterly with scattered convective showers on March 26. Seeding continued at the East Carbon site into the afternoon hours of March 26 before shower activity ended. Precipitation totals were in the 0.5 – 0.8 inch range at the two SNOTEL sites.

A large trough of low pressure over the Great Basin on April 14 brought rain/snow to primarily the northwestern side of the Book Cliffs target area, with a frontal boundary essentially bisecting the area. The southern and eastern portions remained mostly dry with much warmer temperatures. Seeding was conducted from three available sites during the daytime hours to target the northern and western portions of the area in southwesterly flow. The 700 mb temperature was near -4° C in these moisture rich portions of the target area, with some convective activity making conditions favorable for seeding. Seeding operations ended in the evening hours, with precipitation totals ranging up to around a half inch (estimated) in western portions and little if any observed further south and east.

The final seeded event of the season occurred on April 26-27 as a large trough resulted in the development of multiple circulation centers over eastern Utah overnight. Seeding operations began in the evening and continued throughout the afternoon on the 27th, as areas of precipitation continued, including convective showers during the

afternoon. The 700 mb temperature was generally around -4° C, and wind pattern were quite complex although generally favorable for seeding operations. Three sites were operated during this storm period, and SNOTEL sites had precipitation totals of around 0.5 inches of water equivalent.

Figures 7-10 show examples of meteorological data used in the context of seeding operations for the program. These images were archived during the final seeded event of the season in late April. The various products available online are useful for analyzing current conditions as well as forecast conditions, useful for planning seeding site operations.

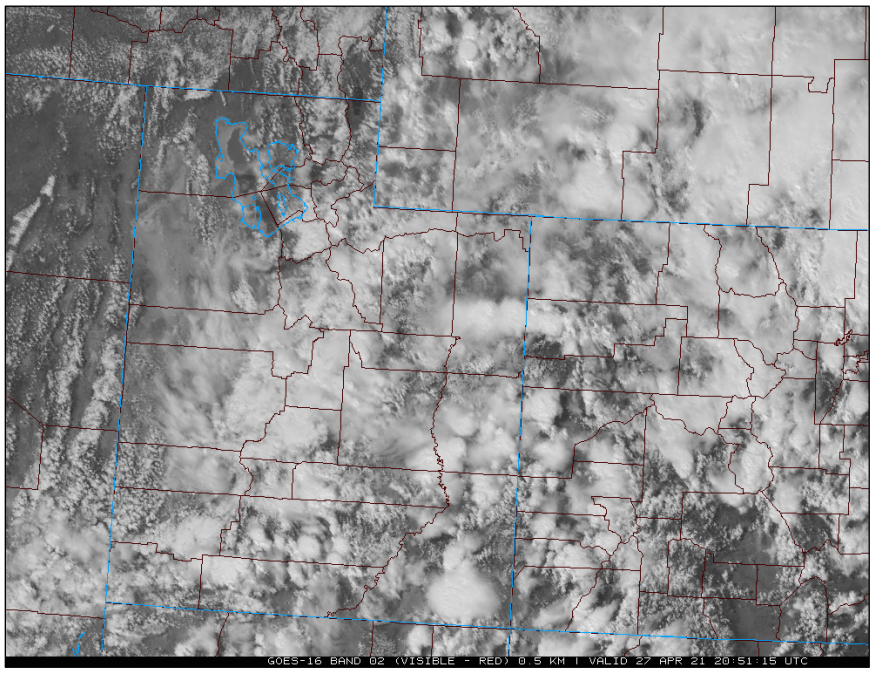


Figure 7 **Visible spectrum satellite image of Utah and Colorado during the early afternoon of April 27, 2021**

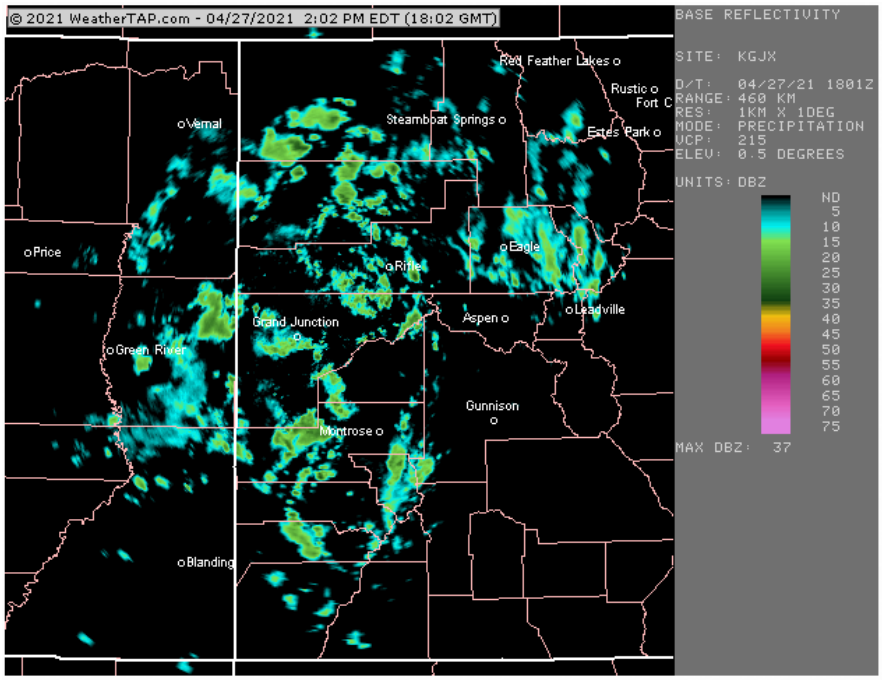


Figure 8 **Radar image from Grand Junction, CO site. Radar coverage is poor in the Book Cliffs area but can occasionally be useful for operations.**

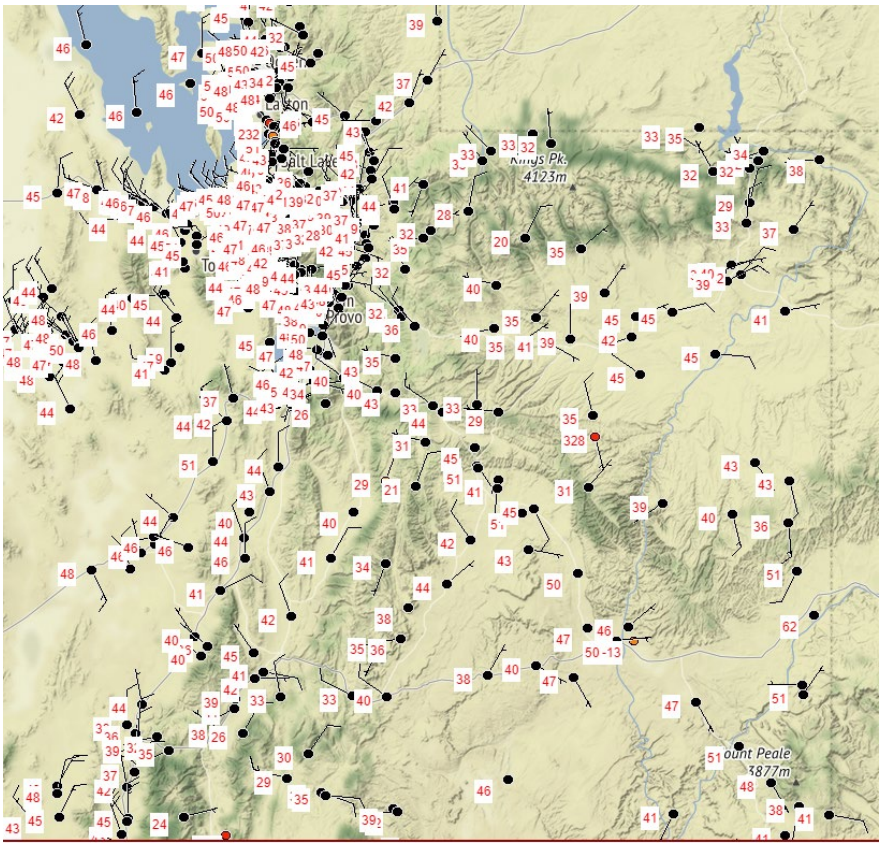


Figure 9 **Surface map showing winds and temperatures across Utah during the April 27 storm event**

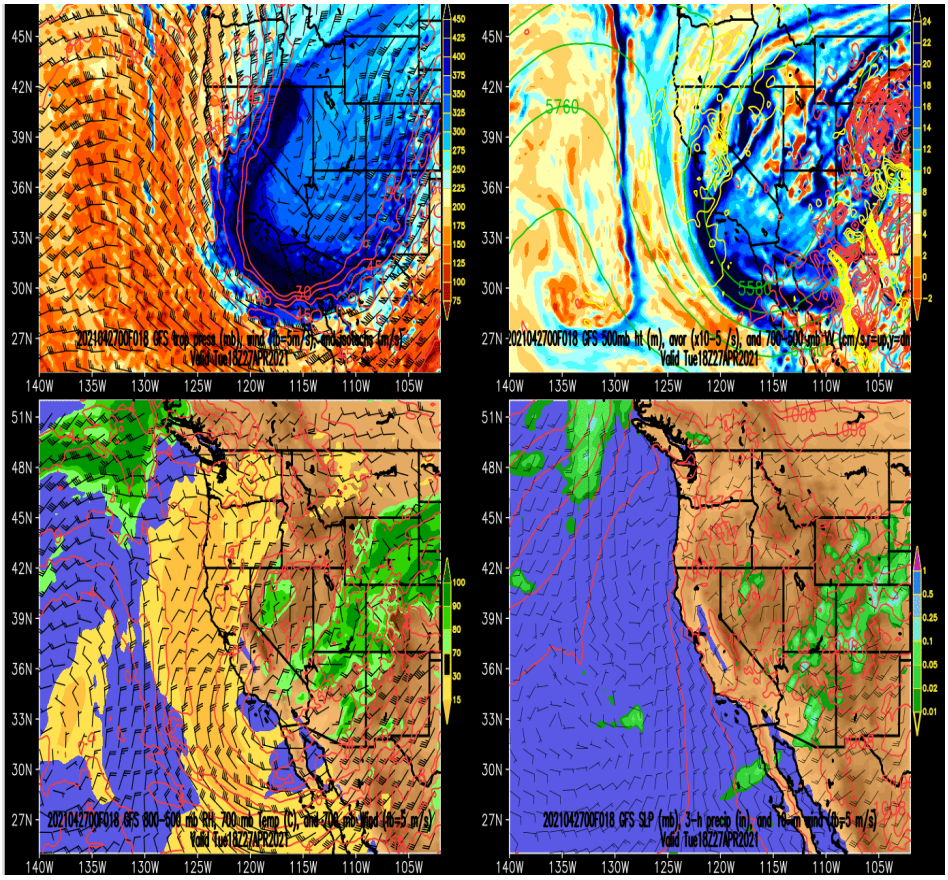


Figure 10 **4-panel plot from the GFS (global) computer forecast model, showing various current and forecast meteorological data fields. These include temperatures, winds, humidity, and projected precipitation among others.**

3.0 TARGET/CONTROL EVALUATIONS

NAWC normally attempts target/control evaluations of its operational cloud seeding programs, utilizing SNOTEL data in and surrounding seeding target areas. This type of evaluation establishes an equation between one or more control sites versus target sites for a historical base period, which is a period of record before the start of a seeding program. This equation is then utilized to produce predicted natural values, in the absence of seeding, which can then be compared to observed values from the seeded periods. SNOTEL sites measure both accumulation water year precipitation from October 1 of each season, and snow water equivalent (SWE) values which normally peaks around March to early April in this area. In a target/control evaluation, the control sites are those which would not be affected by seeding operations for the program being evaluated. The target sites are those within the seeding target area, which may include one or more sites that are expected to be affected by seeding operations.

For the Book Cliffs target area, three potential target SNOTEL sites were considered (see Figure 1 of the introduction section). One of these is Corral SNOTEL, which only has data going back to the 2014 water year. The nearby Timberline site, with data beginning in the 2008 water year. These two sites are near the geographic center of the seeding program target area. The third site, Indian Canyon, is with the only site with a long term record (data beginning in the 1979 water year). However, it is located essentially along the edge of where seeding effects may occur with this program, and so it is not very suitable for either a target or a control site, as it may sometimes (but only occasionally) be affected by seeding.

For the Timberline (target) site, best-correlated control sites were selected that should result in reasonable target/control evaluations using a base (pre-seeding) period that includes water years 2008-2020, a total of 13 seasons. By far the best correlated control site appears to be Mosby Mountain, on the southern flank of the Uinta Range. Although this site is within a seeding program, it has been included in this program consistently during this entire period and continues to be, such that it may still be a suitable control site given the long-term nature of the seeding program there. Another well correlated site is East Willow Creek, located further east on the Tavaputs Plateau. This site is at 8,302 feet, roughly 10 miles east of the Green River, and has data beginning in the 1987 water year. This site would be largely unaffected by the Book Cliffs seeding program. A third control site that was included is Camp Jackson, at 8,858 feet in the Abajo Range of southeastern Utah. This site has a long data record beginning in the 1986 water year. However, the Camp Jackson SNOTEL is located further from the target area, and in a substantially different geographical area. Figure 11 shows the target and control sites selected for this analysis.

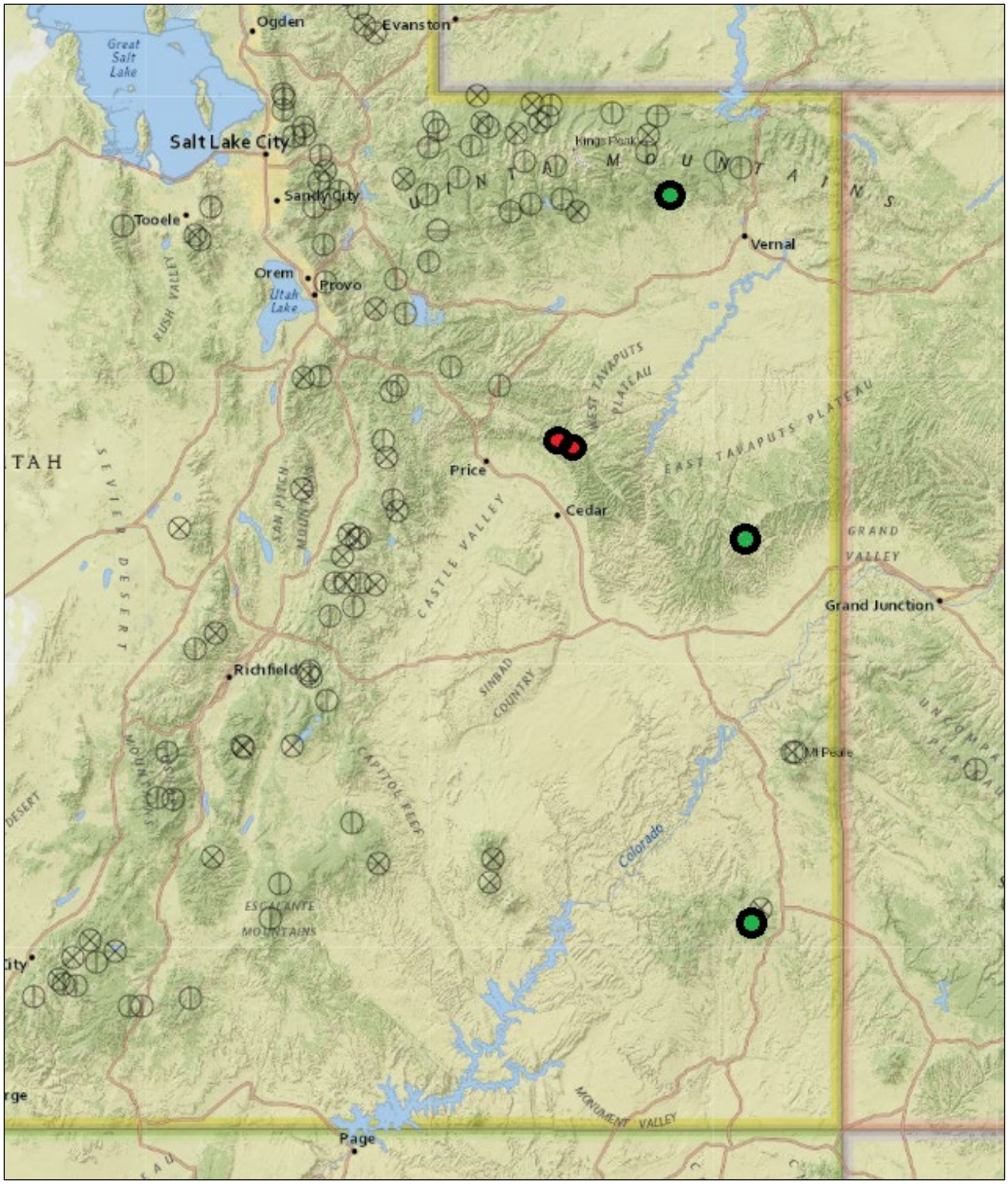


Figure 11 **SNOTEL map of central/eastern Utah with the Book Cliffs evaluation target sites (red) and control sites (green).**

Though evaluation results will not be formally published until after three to five years of consecutive seeding, the equations used to perform the evaluations were developed based on these data sources. Both linear and multiple linear equations were developed. The linear regression compares two variables, in this case an average of the data from three control sites to the target site. The multiple linear regression uses a separate coefficient for each control site, allowing a more complex equation to be developed. For precipitation, the associated R values were high, 0.86 for the linear and 0.95 for the multiple linear. For snow (using SWE), April 1 data is typically used, but some years have a large amount of snow melt prior to this that can essentially invalidate the April 1 SWE for the purposes of this type of evaluation. For this reason, both April 1 and March 1 snowpack were examined. Using the same selection of target and control sites, correlations were good for both with R values of 0.92 and 0.98 (linear/multiple linear) for April 1 SWE and 0.95/0.97 respectively for (linear/multiple linear) evaluations of March 1 SWE.

As only a single season of seeded data is available in the Book Cliffs, data derived from the Uinta Range seeding programs were used to estimate precipitation increases for the Book Cliff seeding program, as was discussed in the feasibility report. Based on this year's precipitation totals during the program (roughly mid-January through the end of April) of about 7.5 inches, it is estimated that an increase of 0.3 inches resulted from cloud seeding efforts in the target area. Though the target area encompasses almost 700,000 acres, for the purpose of estimating precipitation increases, we are only considering the 500,000-acre portion of the target area with the best coverage from the current ground generator network. Applying the 0.3" increase to this portion of the target area results in an estimated increase in seasonal precipitation of 12,500 acre-feet.

4.0 CONCLUSIONS AND RECOMMENDATIONS

A total of eight storm events were seeded in the Book Cliffs during the January – April 2021 season, the first season for the seeding program in this area. There was a total of 350.5 seeding generator hours utilized. Even though precipitation was somewhat below average this season, a number of good seeding opportunities were realized for this program. Based on long-term evaluations for the nearby "High Uinta's" program **an estimated 12,500 acre-feet of additional SWE/Precipitation was produced from cloud seeding efforts in this region.**

With the current regional draught impacting, natural vegetation, crops and animals (particularly livestock), it is particularly important that this program be continued. Given the highly variable nature of precipitation in this region, the program sponsors should consider continuing this program on a regular basis, and not only during drought conditions.

The November – April period is considered to be the seasonal window for potential operations, although certain portions of this period (particularly March – April) are likely to provide the best seeding opportunities for this area in a typical season. NAWC has received preliminary commitments from individuals interested in the downstream benefits of this program to provide funding for the month of December.

Seeding sites should be positioned in areas which are ideal for targeting, based on prevailing wind patterns, and ideally should be above the valley floor to avoid shallow surface-based temperature inversions. It is also important to have site operators who are usually available, in order to effectively utilize the equipment. Land use issues and lack of residents in some areas of Utah can make this a challenge. Maintaining an adequate network of sites and operators should be a priority if the program continues to be active during the 2021-2022 winter season.