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A Multi-facetted Approach to Validating the SAWPA Operational Cloud Seeding Programs

Year 1 Results

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Table of Contents

Tables

TABLE 1. THE PREDICTED PRECIPITATION AND RUNOFF INCREASES FROM THE SAWPA FEASIBILITY STUDY. 8
TABLE 2: SEEDED STORMS WY24 AND ASSOCIATED WEATHER CONDITIONS 11
TABLE 3: NORTHEAST TARGET AREA ESTIMATED PRECIPITATION INCREASES (ALL PERIODS). 23
TABLE 4: NORTHWEST TARGET AREA ESTIMATED PRECIPITATION INCREASES (ALL PERIODS). 23
TABLE 5: SOUTHEAST TARGET AREA ESTIMATED PRECIPITATION INCREASES (ALL PERIODS). 24
TABLE 6: SOUTHWEST TARGET AREA ESTIMATED PRECIPITATION INCREASES (ALL PERIODS). 24
TABLE 7: NORTHEAST TARGET AREA ESTIMATED PRECIPITATION INCREASES (PRECIPITATION OBSERVED). 25
TABLE 8: NORTHWEST TARGET AREA ESTIMATED PRECIPITATION INCREASES (PRECIPITATION OBSERVED). 25
TABLE 9: SOUTHEAST TARGET AREA ESTIMATED PRECIPITATION INCREASES (PRECIPITATION OBSERVED). 26
TABLE 10: SOUTHWEST TARGET AREA ESTIMATED PRECIPITATION INCREASES (PRECIPITATION OBSERVED). 27
TABLE 11: TOTAL ACRE-FEET FROM THE TWO ANALYZED METHODS. 27
TABLE 12: GAUGES USED FOR TARGET CONTROL TASK 4 29

Figures

1 Introduction

The Santa Ana Watershed Project Authority (SAWPA) has funded a 4-year cloud seeding pilot program. The goal of the project is to determine if cloud seeding can generate additional snowfall and rainfall over the Santa Ana Watershed to potentially increase subsequent runoff into the Santa Ana and San Jacinto Rivers (Figure 1). The SAWPA feasibility study identified four primary target areas where cloud seeding would potentially produce additional precipitation and contribute to the area water resources (Figure 2). The Desert Research Institute (DRI) was selected to perform an independent validation of the benefits (i.e. added precipitation) of the program.

As a part of SAWPA's feasibility study, a cloud seeding project was designed primarily based on climatology and plume dispersal models. A set of 58 storms were analyzed to determine the seeding frequency and the potential cloud seeding precipitation increases based on the subjective category of the storm. Finally, a set of regression equations were developed from the data to calculate the potential increases in runoff from a cloud seeding program. Table 1 from the study shows the expected results in the study for an 'average' winter season.

This report creates an preliminary validation approach and summarizes the year-1 validation tasks for the new cloud seeding project areas. The tasks used observed weather (clouds, winds, temperatures), snow chemistry, precipitation, and runoff data sets to validate the seeding operations and the impact to water resources from the cloud seeding program.

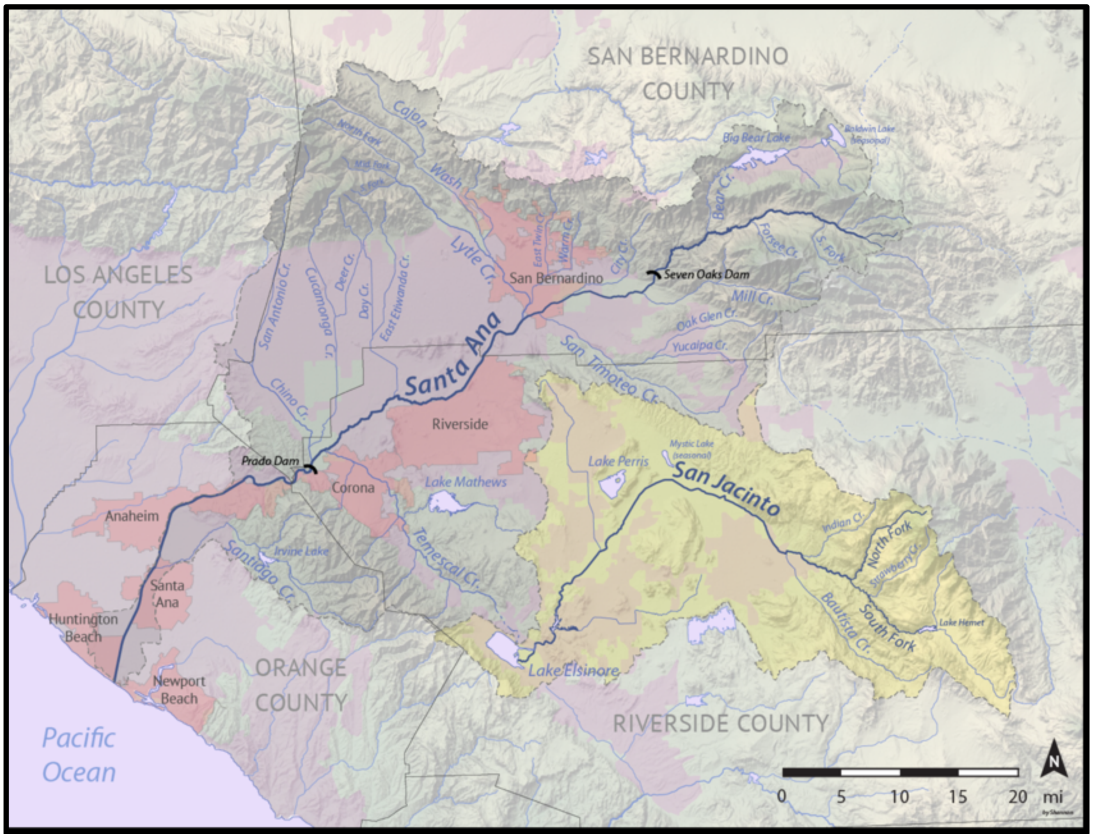

Figure 1. The greater Santa Ana River Watershed.

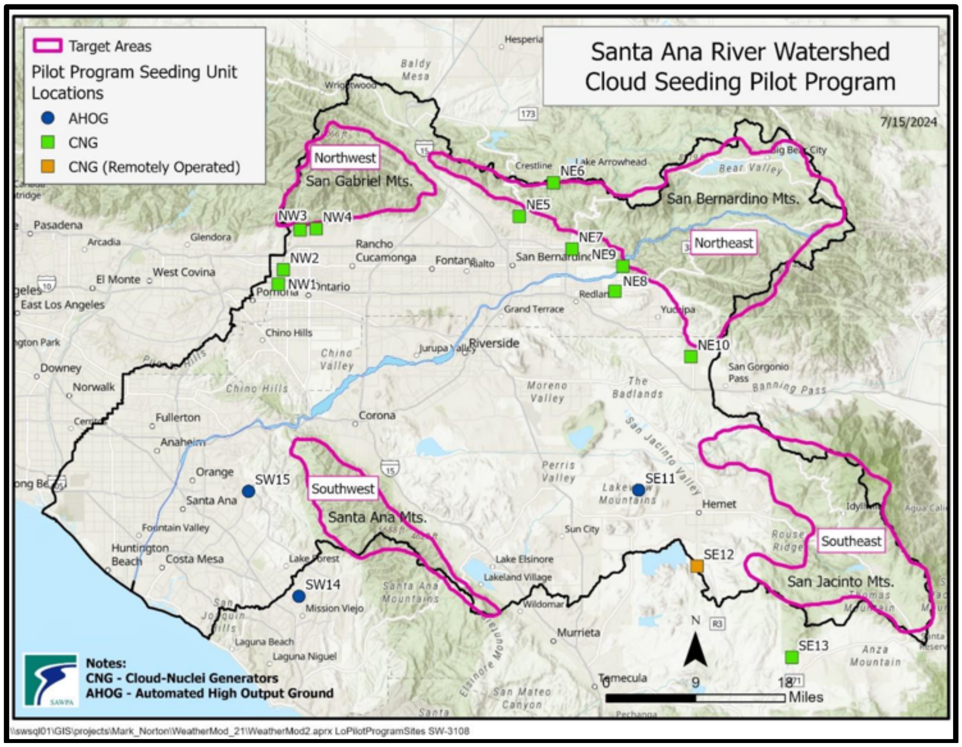

Figure 2: The four SAWPA cloud seeding target areas (enclosed magenta shapes) and generator locations (green rectangles, orange squares, and blue circles) for the Santa Ana River Cloud Seeding Program.

Table 1. The predicted precipitation and runoff increases from the SAWPA feasibility study.

Estimated precipitation and streamflow increases

Target Area	Seasonal Precipitation Increase (inches)	Percent Increase	Avg. Natural Streamflow (AF)	Streamflow Increase (AF)	Percent Increase
NW	0.41	3.5%	25,000	2,043	8.2%
NE (ground)	0.49	4.1%	65,000	4,330	6.7%
NE (air & ground) *	0.89	7.3%	65,000	7,772	12.0%
SW	0.59	3.7%	5,000	447	9.0%
SE	0.49	4.5%	10,000	1,373	13.7%
	TOTAL w/ Ground Only		**105,000**	**8,193**	**7.8%**
	TOTAL w/ Ground and Air		**105,000**	**11,635**	**11.1%**

* This row contains the estimated total or additive impact of both ground and aerial seeding.

2 Cloud Seeding Overview

Successful cloud seeding requires all the components of the ‘chain of events’ be present. The ‘chain of events’ for successful cloud seeding requires: clouds with low bases be present across the target area, the project design must be favorable so that the seeding materials delivered by the cloud seeding generators are able to reach the clouds, the cloud temperatures that the cloud seeding materials interact with must be at or colder than -5ºC, and the clouds must also contain subfreezing liquid water drops (icing conditions). The final requirement is the winds must be favorable to deliver the cloud seeding plume and increased snowfall or rain into the target watershed (Figure 3).

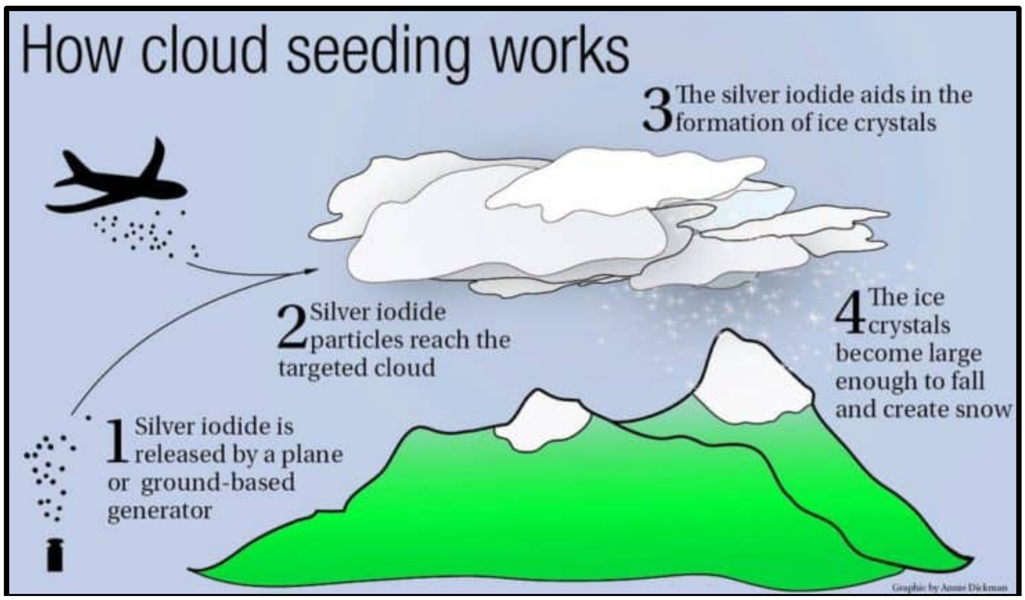

Figure 3: A schematic depiction of the process of cloud seeding

3 Validation

3.1 Overview

Five tasks were proposed in the validation plan for the first year of the operational project.

The goal of Task 1 of this validation is to ensure that the seeding operations are matched to the seedable storm periods. The goal of Task 2 was to assess whether the cloud seeding generator placement is able to deliver seeding material to the target areas (Warburton et. al. 1995). The goal of Task 3 is to determine the estimated amount of additional seeded snowfall/precipitation for each storm, and the winter total in each target area. Task 4 computes the climatological relationship between unseeded seasonal precipitation amounts within the target areas with one adjacent unseeded control area impacted by similar storms and with similar topography. Then the seeded year precipitation was compared to this long-term relationship (Griffiths et. al 2015). Task 5 computes the climatological relationship between the Santa Ana River streamflow and the San Gabriel River streamflow, then compares the seeded year to this long-term relationship (Silverman 2010).

3.2 Task 1. Review Storms Crossing the Area During Operational Winter and Assess the Cloud Seeding Operations

3.2.1 Task 1 Overview

The meteorology of all of the storms crossing the area during winter 2023-2024 were reviewed in detail. The DRI meteorologists independently identified all of the hourly potential seeding and non-seeding storm periods. With all of the seeding periods identified, the seeding operations events performed by SAWPA's operations contractor, NAWC, were then assessed.

3.2.2 Summary of Analysis (Appendix A)

The meteorology of all of the storms crossing the project target area during winter 2023-2024 (WY24) were reviewed in detail and their seeding conditions are summarized in Table 2. A more detailed analysis of each storm is presented in Appendix A. A summary of the analysis and findings follow.

During the month of November 2023 there were no seeding events identified by the DRI meteorologists and only one test run of generators. During the month of December 2023 there were no missed seeding opportunities and two storms were seeded. In January 2024 there were three seeded storms and no missed events. Storms during February produced significant precipitation and the project was suspended during the strong atmospheric river event between February 4-8, 2024. Outside of this suspension, there were two seeding events and no missed seeding opportunities. In March there were three seeded storms with no missed events. Lastly, the first half of April featured two seeded storms and no missed events.

Table 2: Seeded Storms WY24 and associated weather conditions

Storm	Low cloud bases	Favorable wind directions and speeds	Favorable stability for mixing	10,000' MSL temperatures (°C)
Dec 21-22, 2023	Yes	Yes	Yes	-3°C to -4°C
Dec 29-30, 2023	Yes	Yes	Yes	-6°C
Jan 03, 2024	Yes	Yes	Yes	-6°C to -10°C
Jan 20-21, 2024	Yes	Yes	Marginal	-3°C to -5°C
Jan 21-22, 2024	Yes	Yes	Marginal	-3°C
Jan 31- Feb 1, 2024	Yes	Yes	Yes	-3°C to -6°C
Feb 21-22, 2024	Yes	Yes	Yes	-4°C to -5.5°C
Mar 6-7, 2024	Yes	Yes	Yes	-6°C
Mar 23-24, 2024	Yes	Yes	Yes	-6°C to -10°C
Mar 30-31, 2024	Yes	Yes	Yes	-6°C to -8°C
April 5, 2024	Yes	Yes	Yes	-10°C to -12°C
April 13-14, 2024	Yes	Yes	Yes	-6°C

3.2.3 Conclusions

The NAWC meteorologists conducted cloud seeding during 12 storm periods between December 21, 2023 and April 15, 2024. A total of 2,135 generator-hours were completed during the winter across the four target areas. The results from the analysis showed that the NAWC meteorologists seeded when the conditions were suitable and no events were missed. Of the 2,135 generator-hours during the project 1,703 generator-hours occurred during seeding conditions. The 432 generator-hours outside seeding conditions were due to the logistics of operating manual generators.

3.3 Task 2. Targeting Assessment Using Snow Chemistry

3.3.1 Task 2 Methodology

One of the main challenges of conducting cloud seeding from the ground is ensuring that the cloud seeding materials (silver iodide ([AgI]) reach clouds with temperatures colder than -5°C and the newly formed seeded snow is deposited in the target area. Successful targeting can be substantiated by showing slightly elevated silver concentrations in fresh snow. Measurements from the Sierra Nevada and Colorado have shown about 40 parts per trillion for seeded snow compared to about 4 parts per trillion in unseeded. After collecting snow samples during the late 2022-2023 winter right after a cold unseeded storm and assessing the amount of silver in the snow a value of 8 parts per trillion was used as the threshold to delineate between seeded and unseeded snow.

DRI personnel collected snow samples during two winter storm events that occurred between February 20-21, 2024 and March 6-7, 2024. Figure 4 shows the general snow sampling process. Prior to the storms, snow collection tubes were deployed to catch falling snow. Sterile scoops were also used to place fresh snow into ultra clean bags as the seeded storm was winding down. After the storm events, the snow collection tubes with the fresh samples as well as the scooped samples were collected and transported frozen to DRI. The samples remain frozen to minimize any potential contamination due to interactions between the sample and the bag surface. Finally, the samples were analyzed for silver content using the DRI Ultra Trace Chemistry Lab.

If elevated silver values were found in the seeded precipitation collections compared to the unseeded collections, then the generator locations are successfully depositing the seeding material (silver iodide, ice nuclei) in the target area. This would confirm that the generators are well placed to seed the clouds. Collection was done in the Northeast, Northwest, and Southeast target areas. Storm temperatures were too warm for successful snow collection in the Southwest target area and thus no samples were collected from that region.

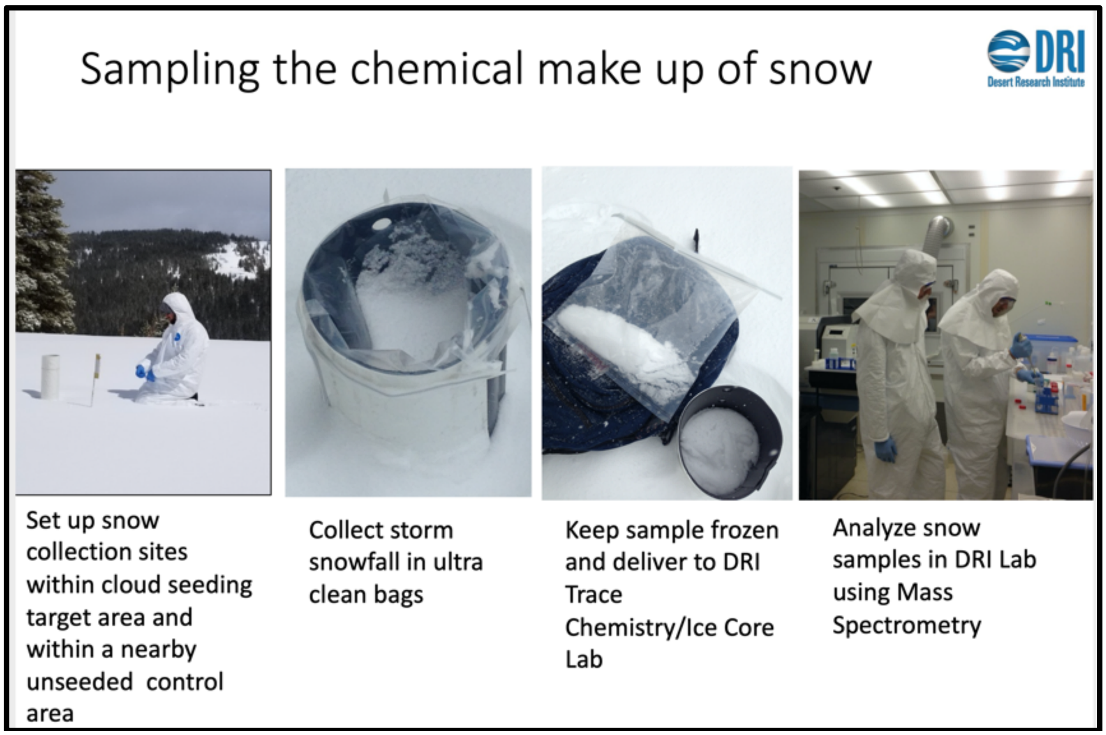

Figure 4: DRI snow chemistry collection and analysis methods

3.3.2 Snow Chemistry Collection Case Analysis

3.3.2.1 Snow Chemistry Case 1: February 20-21, 2024 (Northeast and Northwest)

On February 20, 2024 a weak trough and associated cold front was approaching the southern California coast. A moist southwesterly flow was present across the northeast and northwest portions of the project area as seen in the weather map in Figure 5. Snow collection sites were identified and collection tubes were installed prior to the start of the storm during the morning and early afternoon of February 20. The trough and cold front moved across the area over night, with much of the area clearing by midday on February 21, 2024. The 3 tubes were collected midday on the February 21, 2025, and two additional 10-inch depth sterile scoops were also collected. The locations of the collection sites are shown in Figure 6.

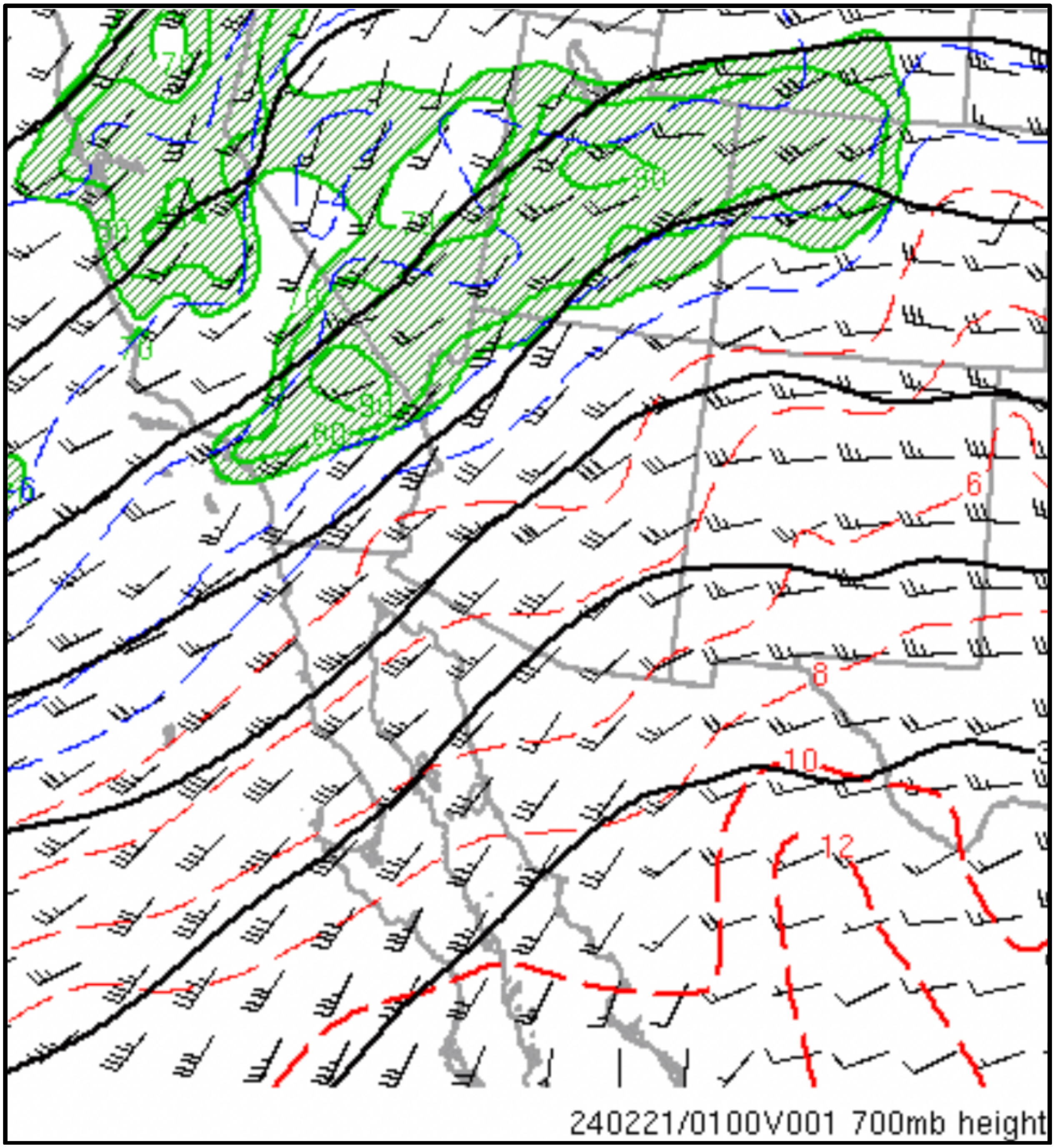

Figure 5: 700 mb (10,000' MSL) weather map valid at 1700 Feb 20, 2024. Winds barbs, temperatures (red and blue), moisture (green shading), and geopotential height (black lines).

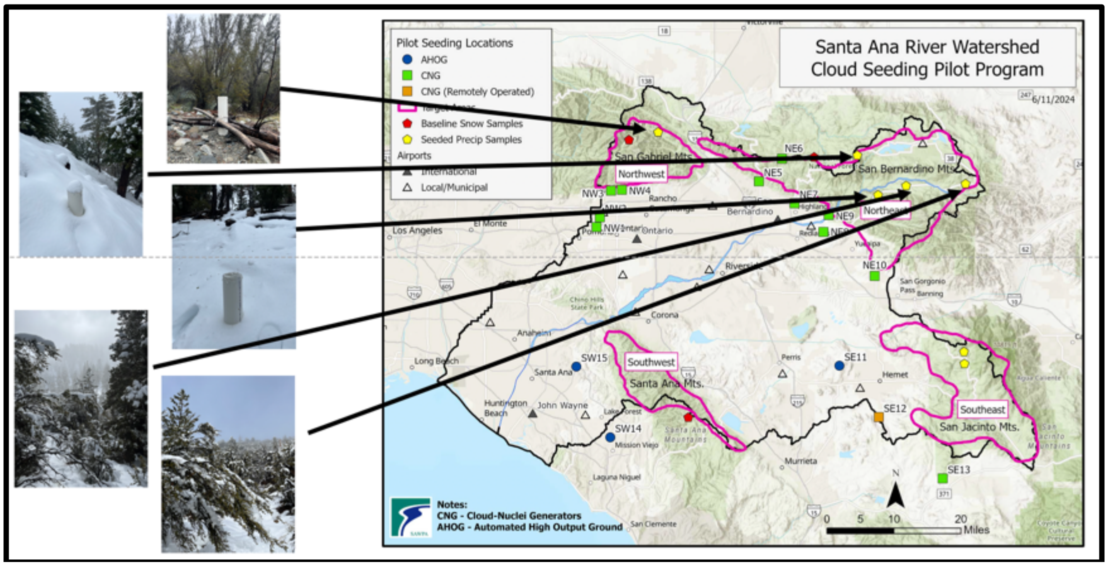

Figure 6: Map of precipitation collection sites.

3.3.2.2 Case 1 Results

An analysis of winds and dispersion using the Hysplit plume model, as seen in Figure 7, showed that the collection locations could have been impacted by the seeding plume released from the generators. The measurements from the snow analysis are shown in Figure 8. Of the 5 samples collected, most had low to below detectable levels of silver. The site above Angelus Oaks measured 9.5 ppt which is slightly above the no-seed snow concentration threshold of 8 ppt.

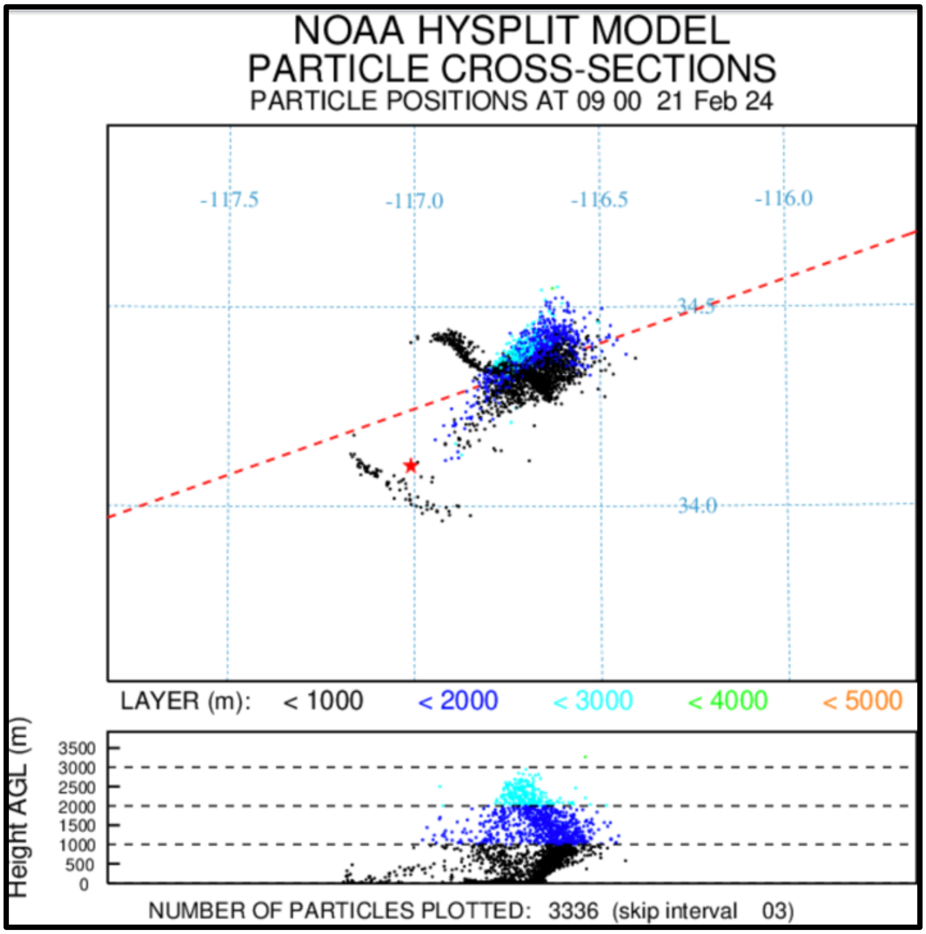

Figure 7: Three-hour horizontal and vertical cross-section Hysplit simulation of released plume from the NE8 generator between 2300 Feb 20, 2024 and 0200 Feb 21, 2024. The -5°C level was at 9,000-ft.

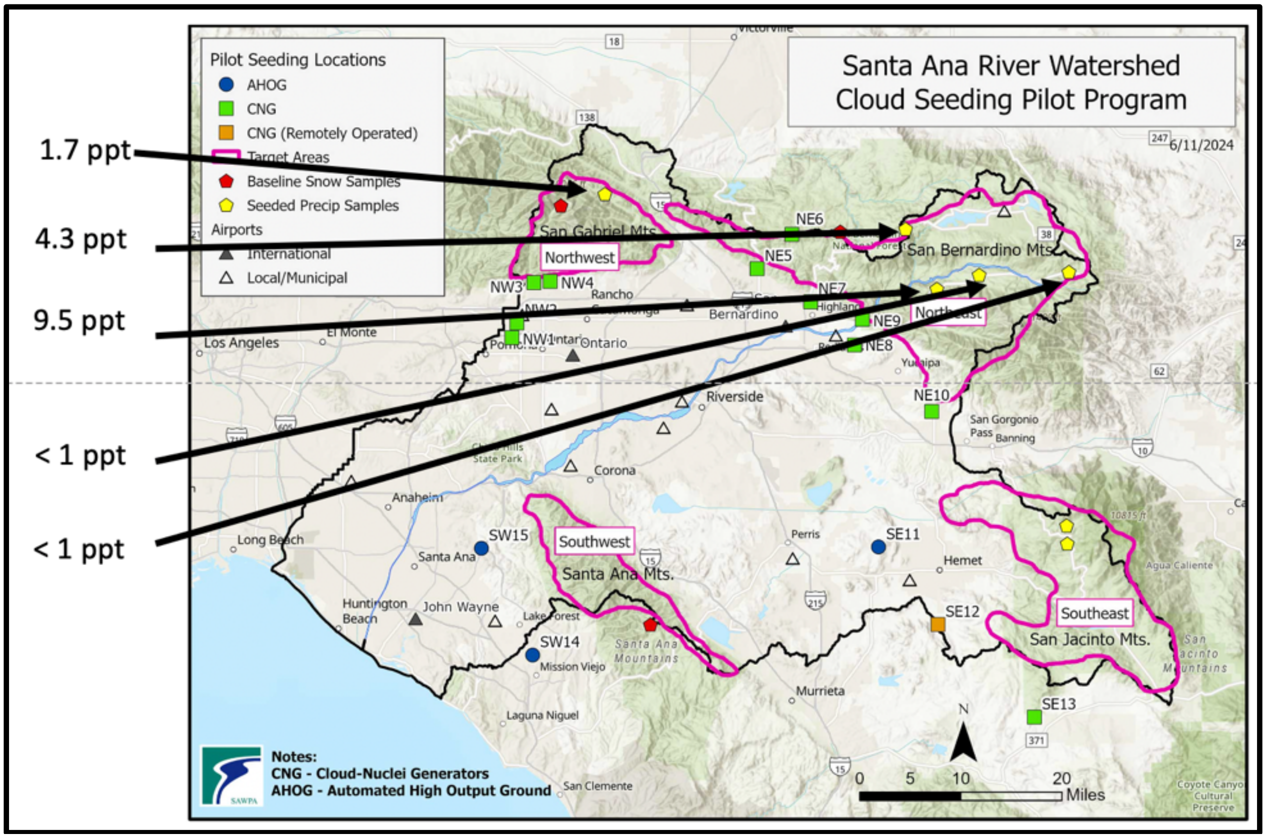

Figure 8: Snow Chemistry Results for February 20-21, 2024

3.3.2.3 Snow Chemistry Case 2: March 6-7, 2024 (Southeast)

On March 6, 2024 a trough and associated upper-level cold pool were approaching the southern California coast (Figure 9). A moist unstable west-southwesterly flow was present across the southeast project area. Snow collection sites were identified and two collection tubes were installed prior to the start of the storm in the Southeast region during the early afternoon of March 6 (Figure 10). The trough and cold pool moved across the area over night, with much of the area clearing by late in the day on March 7, 2024. The tubes were collected early on March 8, 2024. The hysplit model showed that tubes would have been successfully targeted by the cloud seeding generators (Figure 11), but based on the vertical motions predicted by the mode the plume may not have mixed to the -5°C level.

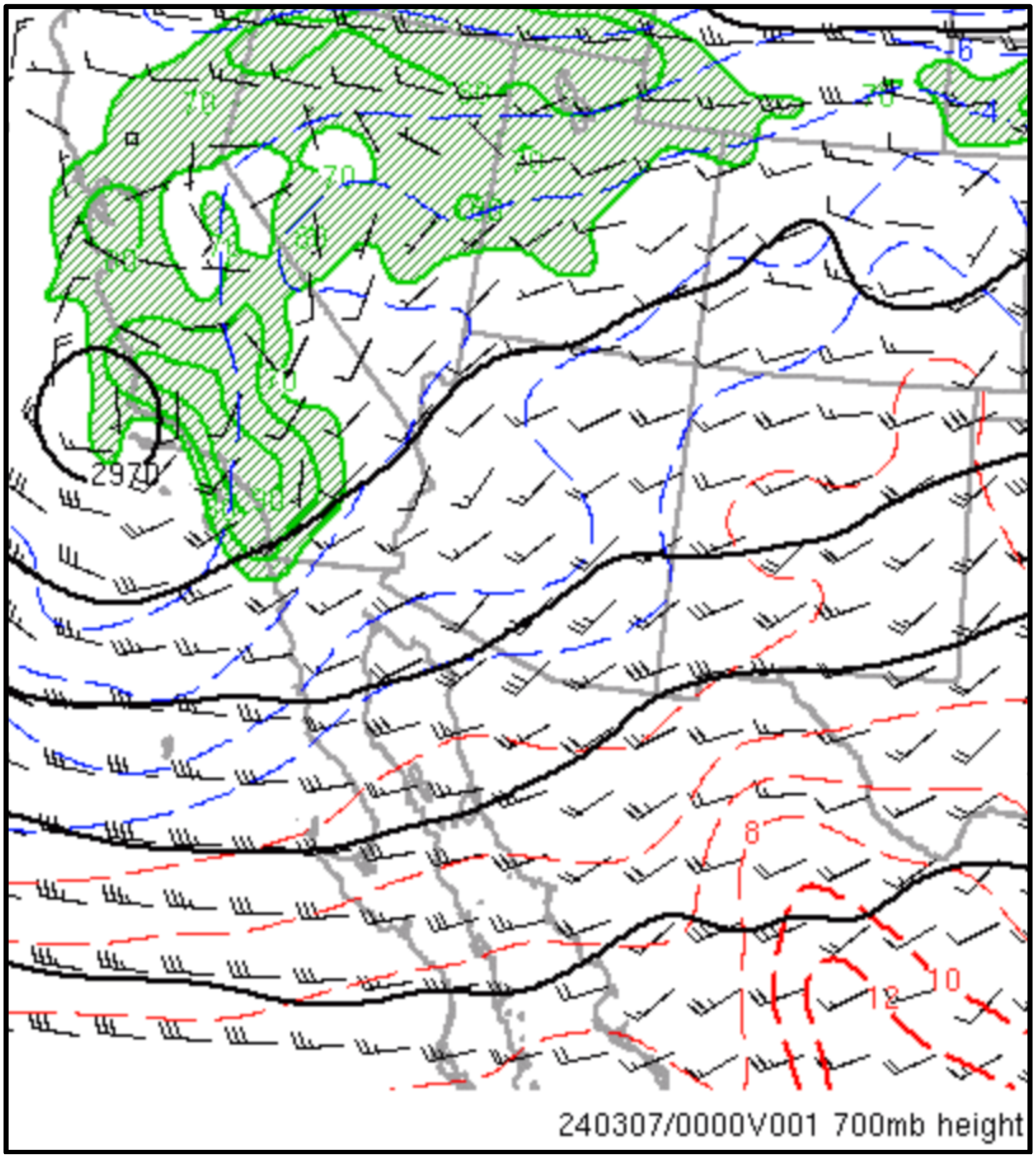

Figure 9: 700 mb (10,000' MSL) weather map valid at 1700 Mar 6, 2024. Winds barbs, temperatures (red and blue), moisture (green shading), and geopotential height (black lines).

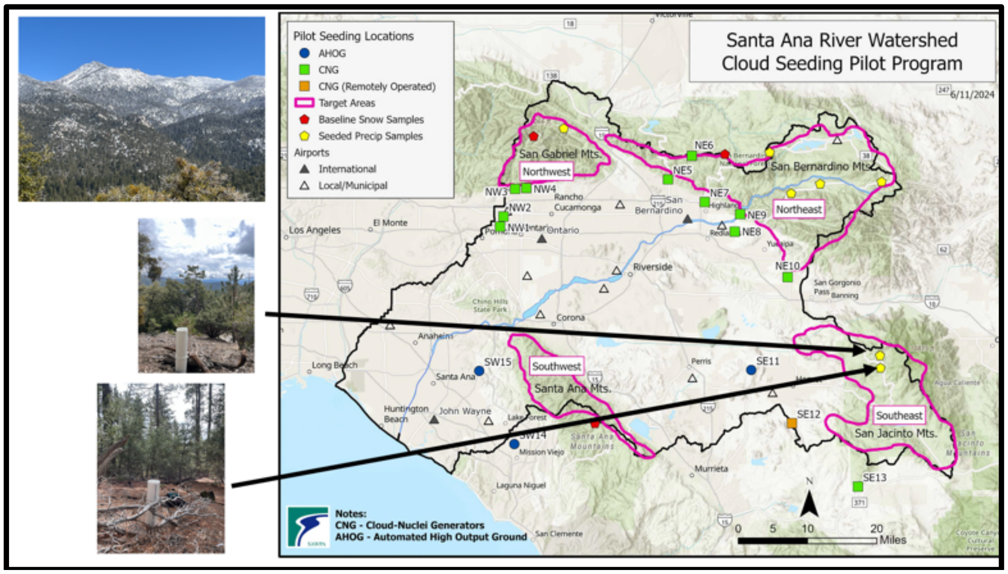

Figure 10: Map of precipitation collection sites.

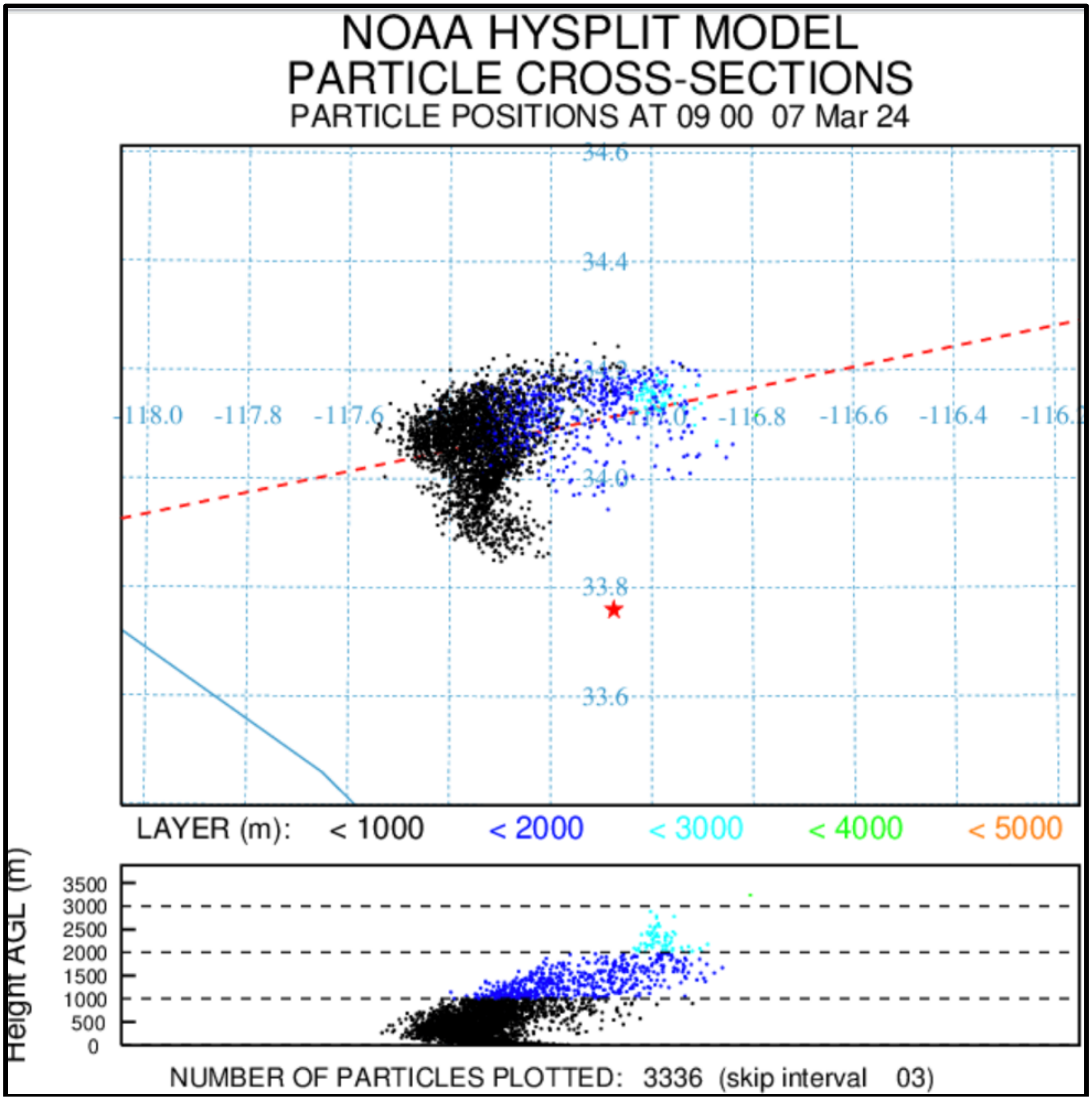

Figure 11: Three-hour horizontal and vertical cross-section Hysplit simulation of released plume from the NE8 generator between 1200 March 6, 2024 and 0800 March 08, 2024. The -5oC level was at 9,000

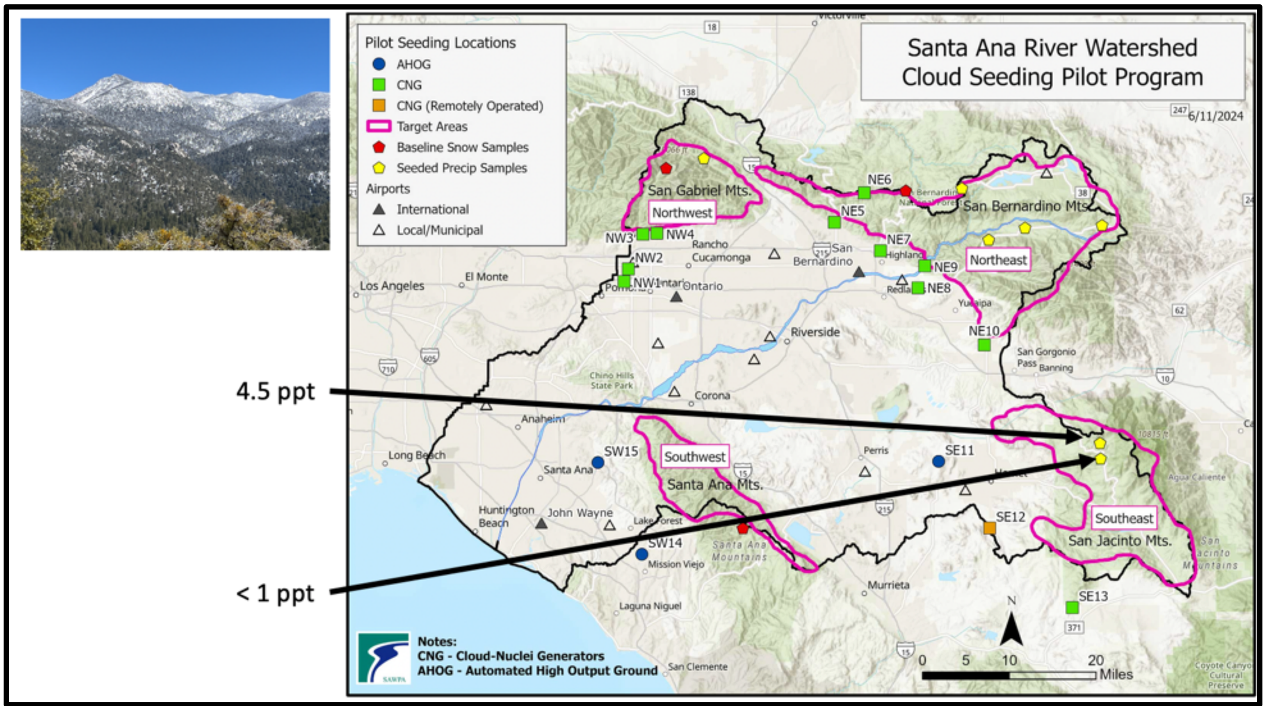

Figure 12: Snow Chemistry Results for March 6-7, 2024

3.3.2.4 Case 2 Results

The results of the analysis showed low to below detectable limit amounts of silver in the two snow samples collected (Figure 12). A largest measurement of 4.5 ppt that was observed at one of the collection sites is lower than the 8 ppt threshold delineates between seeded and unseeded snow and is close to what has previously been observed in unseeded snow samples from the Sierra and Colorado.

3.3.3 Task 2 Results Summary

The snow chemistry field work sampled two storms within the northwest, northeast and southeast target areas. The southwest target area was not sampled due to warm temperatures and lack of seeding.

Seven samples were collected during the two seeded storms. The Hysplit model was used to confirm that the seeding plume could have moved into the sampled target areas. The results of the snow chemistry analysis showed very low values of silver in most of the samples, suggesting that the seeding plume was not depositing silver iodide ice nuclei at the collection locations. One sample near Angelus Oaks contained 9.5 ppt of silver that is higher than the 8 ppt threshold used to delineate between seeded and unseeded snow. This value, while not as high as values previously observed in seeded snow samples taken in the Sierra and Colorado of around 40 ppt, does potentially show successful targeting.

The low silver values found compared to the Sierra projects don't necessarily suggest that seeding wasn't successful. The seeding plumes from the ground-based generators are typically narrow and although the targeted clouds are impacted, the limited number of storms sampled (1) may have allowed the plume to miss the collection tubes.

We recommend running high-resolution modeling and plume modeling for the winter 2023-2024 seeded storms. This will provide much more realistic terrain and horizontal dispersion of the simulate cloud seeding plume. sampling of silver output near the generators and additional precipitation target areas during three storms. This should be conducted during the next winter when the program is operational.

3.4 Task 3. Estimating the Seeding Snow Water Equivalent (SWE) or Rainfall Increases for Each of the Seeded Storms.

3.4.1 Background

Huggins (2009) summarizes studies across the western US which document the cloud seeding chain of events. The studies used research aircraft, microwave radiometers, mountain top icing detectors, and other instruments to document the availability of subfreezing liquid water (SLW). The studies showed that periods with clouds containing SLW were present in nearly every winter storm. The SLW was predominately present over the windward slopes of the mountains, and the zone of maximum SLW extends from below the mountain crest to 1 km above the mountain crest. The paper also references studies using microwave radiometer measurements of SLW that showed that the total flux of SLW across a mountain barrier, if converted to precipitation, could increase the observed seasonal snowpack by 50% - 100%.

Successful cloud seeding depends on there being an excess of SLW in winter storms, and that the SLW exists at low enough temperatures for seeding material to be effective. The overall conclusion of every study of SLW availability was that significant cloud seeding potential existed in winter storms over mountainous terrain provided the proper seeding technique could be applied at the appropriate time and location.

In the late 1980s techniques were used to document very consistent and successful transport and dispersion of cloud seeding material over the Grand Mesa in Colorado (Holroyd et al. 1988; Super and Boe, 1988) from both ground-based and aircraft releases of silver iodide. Additional verification of successful transport and dispersion of ground-released seeding material has been documented over the Wasatch Plateau in Utah (Holroyd et al., 1995). These and other transport and dispersion studies during the 1980s and 1990s began to include early high-resolution model simulations of plumes that were verified by observations. Additional examples include Sierra Nevada studies (Meyers et al., 1995) and Arizona experiments (Bruintjes et al., 1995).

Measurements which verified the initiation, growth and fallout of ice crystals were included in many of the experiments involved with tracking silver iodide seeding plumes. Some of the first evidence of this type was documented in the Bridger Range Experiment (BRE) (Super and Heimbach, 1988). For clouds containing SLW it was found that ice particle concentrations were significantly enhanced and estimates of precipitation in seeded regions exceeded natural clouds by factors of two or more.

Seeding plume locations, ice particle enhancement, and precipitation increases within seeding plumes were carefully documented in four papers (Holroyd et al., 1995; Super and Holroyd, 1997; Huggins, 2007; Holroyd et al., 1998)

In the BRE the best results from AgI seeding came from the colder cases (Super, 1999). Further evidence of the evolution of ice particles in seeding plumes released by aircraft was provided by cloud seeding experiments over the Sierra Nevada of California (Deshler et al., 1990.).

Another randomized experiment was conducted by the Pacific Gas and Electric (PG&E) Company in a region near Lake Almanor in the northern Sierra Nevada (Mooney and Lunn, 1969). A statistically significant result came from a cold-westerly storm stratification where a 32% increase in precipitation was indicated for seeded cases. Trace chemical evaluations of snowfall in the Lake Almanor project area (Warburton et al., 1995a, and 1995b) have since helped substantiate the statistical indications. A common finding from the projects referenced here is that the most pronounced seeding effect occurred in relatively cold and shallow orographic clouds. Evidence indicated that precipitation can be increased by 50% or more in these storm periods, which can result in seasonal increases of snowfall by the approximately 10% augmentation that is quoted in capability statement of the American Meteorological Society (Amer. Meteor. Soc., 1998).

One operational program in the central Sierra Nevada used this trace chemical technique to show that cloud seeding operations produced a seasonal 8% increase in the snowpack over the South Fork of the San Joaquin River (McGurty, 1999).

3.4.2 Precipitation Estimation Analysis

The precipitation increases from the individual storms were estimated using two different techniques.

The first method uses the number of DRI identified seeding hours and assumes a conservative 0.01-inch (liquid equivalent if the precipitation is in the form of snow) increase in precipitation per hour under each of the generators seeding plumes. DRI high-resolution plume modeling from other studies suggest that the generator plume impact area is ~30 square miles (20-miles long by 1.5-miles wide). Since it is possible that the increased seeded precipitation is not impacting any of the precipitation gauges, all of the generator hours are considered. This technique is generous in its estimate due to assuming precipitation increases for all active seeding hours present, but also is conservative due to the estimate of 0.01” per hour. The warmer and high liquid water content clouds found over southern CA could lead to seeding increases up to approximately 0.03” per hour in real conditions.

Method Two assumes that seeding is only successful if precipitation is observed within the target area at a gauge. The seeding is assumed to have contributed 10% of the precipitation observed during the times when seedable clouds are over the area and the generators are active.

3.4.2.1 Precipitation Estimation - Method One

First it was assumed a 0.01” per hour increase in precipitation along the terrain under generators footprint (30 sq mi) during the time periods when seedable conditions were present, *(Seeded precipitation) X (impacted area) = (acre-feet of additional water resources from seeding).* This method is likely an over estimate as it assumes all the times when seedable conditions were present were successfully seeded.

The precipitation estimates using method one for the four target areas are shown in the tables below. The northeast target area saw an increase of 15,428 acre-ft of precipitation (Table 3), the northwest target area saw an increase of 8,060 acre-ft.

Table 4), the southeast target area saw an increase of 4,210 acre-ft (Table 5), and the southwest target area saw an increase of 700 ac-ft (Table 6).

Table 3: Northeast target area estimated precipitation increases (all periods).

Storm	Seeding Hours	Flares during seeding	Estimated Increased Precipitation (acre-feet)
Dec 21-22, 2023	80.50	NA	1288
Dec 29-30, 2023	47.50	NA	760
Jan 03, 2024	49.25	NA	788
Jan 20-21, 2024	105.25	NA	1684
Jan 21-22, 2024	99.75	NA	1596
Jan 31- Feb 1, 2024	39.00	NA	624
Feb 21-22, 2024	80.00	NA	1280
Mar 6-7, 2024	82.50	NA	1320
Mar 23-24, 2024	63.00	NA	1008
Mar 30-31, 2024	157.25	NA	2516
April 5, 2024	80.25	NA	1284
April 13-14, 2024	80.00	NA	1280
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Total	964.25		15428

Table 4: Northwest target area estimated precipitation increases (all periods).

Storm	Seeding Hours	Flares during seeding	Estimated Increased Precipitation (acre-feet)
Dec 21-22, 2023	24	NA	384
Dec 29-30, 2023	31	NA	496
Jan 03, 2024	19.25	NA	308
Jan 20-21, 2024	0	NA	0
Jan 21-22, 2024	0	NA	0
Jan 31- Feb 1, 2024	42.75	NA	684
Feb 21-22, 2024	144.50	NA	2312
Mar 6-7, 2024	44.00	NA	704

Mar 23-24, 2024	48.00	NA	768
Mar 30-31, 2024	84.50	NA	1352
April 5, 2024	39.50	NA	632
April 13-14, 2024	26.25	NA	420
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Total	503.75		8060

Table 5: Southeast target area estimated precipitation increases (all periods).

Storm	Seeding Hours	Flares during seeding	Estimated Increased Precipitation (acre-feet)
Dec 21-22, 2023	14.75	5 (250 ac-ft)	486
Dec 29-30, 2023	12.00	0	192
Jan 03, 2024	17.75	0	284
Jan 20-21, 2024	15.25	0	244
Jan 21-22, 2024	14.25	4 (200 ac-ft)	228
Jan 31- Feb 1, 2024	26.25	1(50 ac-ft)	420
Feb 21-22, 2024	0	0	0
Mar 6-7, 2024	29.75	0	476
Mar 23-24, 2024	27.50	0	440
Mar 30-31, 2024	55.75	1 (50 ac-ft)	892
April 5, 2024	21.75	0	348
April 13-14, 2024	0	0	0
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Total	235.00	11 (550 ac-ft)	4210

Table 6: Southwest target area estimated precipitation increases (all periods).

Storm	Seeding Hours	Flares during seeding	Estimated0Increased Precipitation (acre-feet)
Dec 21-22, 2023	-	1 (50 ac-ft)	50
Dec 29-30, 2023	-	3 (150 ac-ft)	150
Jan 03, 2024	-	0	0
Jan 20-21, 2024	-	1 (50 ac-ft)	50
Jan 21-22, 2024	-	3 (150 ac-ft)	150
Jan 31- Feb 1, 2024	-	1(50 ac-ft)	50
Feb 21-22, 2024	-	0	0
Mar 6-7, 2024	-	3 (150 ac-ft)	150
Mar 23-24, 2024	-	0	0
Mar 30-31, 2024	-	2 (100 ac-ft)	100
April 5, 2024	-	0	0

April 13-14, 2024	-	0	0
==============	==============	==============	==============
Total	-	14 (700 ac-ft)	700

3.4.2.2 Precipitation Estimation - Method Two

The second method of precipitation estimation assumes that seeding was successful only if measurable precipitation was observed within the target area during seeding periods. This method assumes a 10% increase in precipitation along the terrain under generators footprint (30 sq mi) during the time periods when seedable conditions were present and precipitation was observed.

The precipitation estimates using method 2 for the four target areas are shown in the tables below. The northeast target area realized an increase of 6,017 acre-ft of precipitation (Table 7), the northwest target are saw an increase of 3,138 acre-ft (Table 8), the southeast target area saw an increase of 1,754 acre-ft (Table 9), and an increase of 155 ac-ft was seen for the southwest target area (Table 10).

Table 7: Northeast target area estimated precipitation increases (precipitation observed).

Storm	Precipitation during seeding	Estimated Precipitation increases during seeding (10%)	Number of generators	Estimated Precipitation increases acre feet;
Dec 21-22, 2023	0.31”	0.031”	6	298
Dec 29-30, 2023	0.29”	0.029	6	278
Jan 03, 2024	0.26”	0.026”	6	250
Jan 20-21, 2024	0.67”	0.067”	6	643
Jan 21-22, 2024	1.43”	0.143”	5	1373
Jan 31- Feb 1, 2024	1.12”	0.112”	4	717
Feb 21-22, 2024	0.36	0.036”	4	230
Mar 6-7, 2024	0.40	0.040”	5	320
Mar 23-24, 2024	0.27	0.027”	6	259
Mar 30-31, 2024	1.22”	0.12”	5	960
April 5, 2024	0.23	0.023	6	221
April 13-14, 2024	0.80	0.080	6	768
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Total	7.36”	0.736		6,017

Table 8: Northwest target area estimated precipitation increases (precipitation observed).

Storm	Precipitation during seeding	Estimated Precipitation	Number of generators	Estimated Precipitation

		increases during seeding (10%)		increases acre feet;
Dec 21-22, 2023	0.79”	0.079”	2	253
Dec 29-30, 2023	0.17”	0.017”	4	109
Jan 03, 2024	0.39”	0.039”	3	187
Jan 20-21, 2024	1.02”	0.102”	0	0
Jan 21-22, 2024	1.76”	0.176”	0	0
Jan 31- Feb 1, 2024	2.06”	0.206”	3	989
Feb 21-22, 2024	0.00”	0.000”	3	0
Mar 6-7, 2024	0.00”	0.000”	3	0
Mar 23-24, 2024	0.33”	0.033”	4	211
Mar 30-31, 2024	1.96”	0.196”	3	941
April 5, 2024	0.00”	0.000”	4	0
April 13-14, 2024	0.70	0.070”	4	448
=========	=========	=============		============
Total	9.18”	0.918		3,138

Table 9: Southeast target area estimated precipitation increases (precipitation observed).

Storm	Precipitation during seeding	Precipitation increases during seeding (10%)	Number of generators (flares)	Precipitation increases acre feet;
Dec 21-22, 2023	0.25”	0.025”	2 (5)	80
Dec 29-30, 2023	0.46”	0.046”	2	147
Jan 03, 2024	0.43”	0.043”	2 (2)	187
Jan 20-21, 2024	0.84”	0.084”	1	134
Jan 21-22, 2024	0.98”	0.098”	1	157
Jan 31- Feb 1, 2024	1.05”	0.105”	2	336
Feb 21-22, 2024	0.00”	0.000”	0	0
Mar 6-7, 2024	0.44”	0.044”	2 (1)	140
Mar 23-24, 2024	0.00”	0.000”	0	0
Mar 30-31, 2024	1.41”	0.141”	2	541
April 5, 2024	0.10”	0.010”	2	32
April 13-14, 2024	0.48”	0.048”	0	0
=========	=========	=============		============
Total	6.44”	0.644		1754

Table 10: Southwest target area estimated precipitation increases (precipitation observed).

Storm	Precipitation during seeding	Precipitation increases during seeding (10%)	Number of generators (flares)	Estimated Precipitation increases acre feet;
Dec 21-22, 2023	0.28”	0.028”	(1)	44.8
Dec 29-30, 2023	0.10	0.010”	(3)	16
Jan 03, 2024			-	0
Jan 20-21, 2024	0.26”	0.026”	(1)	41.6
Jan 21-22, 2024	0.10”	0.010	(3)	16
Jan 31- Feb 1, 2024			-	0
Feb 21-22, 2024			-	0
Mar 6-7, 2024	0.06”	0.006”	(3)	9.6
Mar 23-24, 2024			-	0
Mar 30-31, 2024	0.27”		(2)	43.2
April 5, 2024				0
April 13-14, 2024				0
=========	========	============		===========
Total	1.07”		(14) flares	172.2

3.4.3 Precipitation Estimation Results Summary

Two different precipitation estimation methods to estimate the increases in precipitation were presented (Table 11). These methods are derived from much of the previous work by Huggins (2009). The first method assumes that cloud seeding is successful if the generators are operational and seeding conditions are present. This may be an overestimate, or best-case scenario. This method suggests that as much as 28,000 acre-feet of additional precipitation was added to the watershed from the cloud seeding program.

The second method required that precipitation be observed at a gauge within the target area while cloud seeding is active. It also assumed that 10% of the precipitation was generated from the seeding program. This method may be an underestimate since the gauges may not be in the most active precipitation terrain. The second method suggests that over 11,000 acre-feet of additional precipitation was added to the watershed.

Table 11: Total Acre-feet from the two analyzed methods.

Target Area	Seedable Clouds Present (acre-ft)	Seedable Clouds and Precipitation Present (acre-ft)
Northeast	15,428	6,017
Northwest	8,060	3,138

Southeast	4,210	1,754
Southwest	700	172
======================	=======================	=====================
All	27,698	11,081

3.5 Task 4. Precipitation, Full Seasonal Target-Control Evaluation

3.5.1 Overview and Methodology

The goal of Task 4 is to identify if the seeding operations estimated increase the measured precipitation at gauges within the greater target areas when compared to the unseeded climatological relationship developed between the precipitation amounts at these gauges paired with a control gauge outside the greater target area where seeding did not occur. In order to determine this, gauges with at least 12 years of data were identified both inside and outside the target areas.

Since most of the precipitation that falls across the four target areas is accompanied by low-pressure systems moving onshore with counterclockwise flow, the target areas precipitation climatology and project design require south through west-southwesterly winds when cloud seeding conditions are present. As the storms move on shore the gauge site at the Sana Rosa Plateau remains upwind of all seeding locations, therefore this was identified as the most favorable control site. Eleven gauges were identified within the four target areas, and one gauge was identified north of the project area to assess the impact outside the target area. Table 12 lists all the gauge identifiers and names along with their elevation and target area they are associated with. Figure 14 shows a map with the locations of the gauges and target areas identified.

Each gauge within the target areas was paired with the control gauge. A climatology was developed by pairing the total precipitation at both gauges from November 1 through April 30 for each of the 12 water years between 2012 – 2023 to create a non-seeded seasonal relationship. The yearly total precipitation pairs were then plotted with the control site value on the x-axis and the target site value on the y-axis. A linear regression on the paired yearly precipitation totals was performed for each of the 12 sites over the non-seeded 12 years. This created the non-seeded relationship for each site pair. Finally, the total precipitation matched pair for each of the target-control gauges for WY24 is plotted and compared to the relationship created for that gauge.

While one year is not enough data to say if there is a definitive impact from cloud seeding, if the WY24 value is plotted above the regression line for the non-seeded relationship then there is a potential that the seeding had a positive effect when compared to the climatological average. If the value is below the regression line, then the seeding did not appear to increase the precipitation at the gauge for WY24 compared with the climatological average. This decrease can be due to year to year or storm to storm variability. A point on the regression line would indicate no change. More data than one year would be needed to assess the success of the project.

The target and control evaluation for each of the four target areas winter season precipitation is shown below.

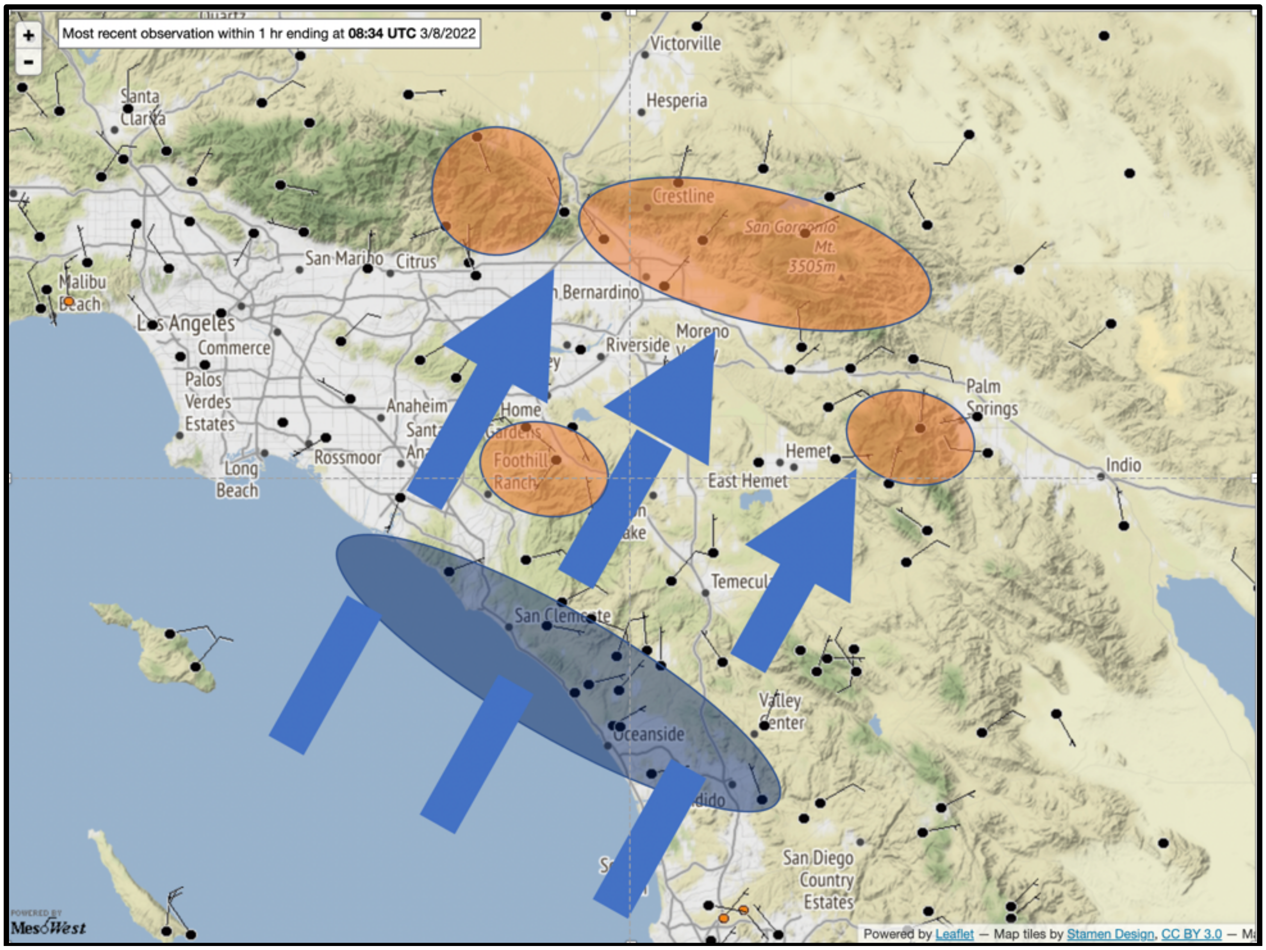


Figure 13: Target-Control upstream,

Table 12: Gauges used for target control task 4

Gauge Identifier	Gauge Name	Elevation (ft)	Associated Area
BCNC1	Burns Canyon	6,394	Northeast
BCFC1	Big Pine Flat	6,851	Northeast
FWSC1	Fawnskin	6,900	Northeast
RCPC1	Rock Camp	4,923	Northeast
HHPC1	Heaps Peak	6,455	Northeast
CVEC1	Converse	5,618	Northeast
LTLC1	Lytle Creek	2,792	Northwest
VGRC1	Vista Grande	4,906	Southeast
KNWC1	Keenwild	4,752	Southeast
KWYC1	Kenworthy	4,590	Southeast
IVLC1	Silverado	1,105	Southwest

SRUC1	Santa Rosa Plateau	1,987	Control
MVDC1	Mojave Dam	3,134	Extra Area

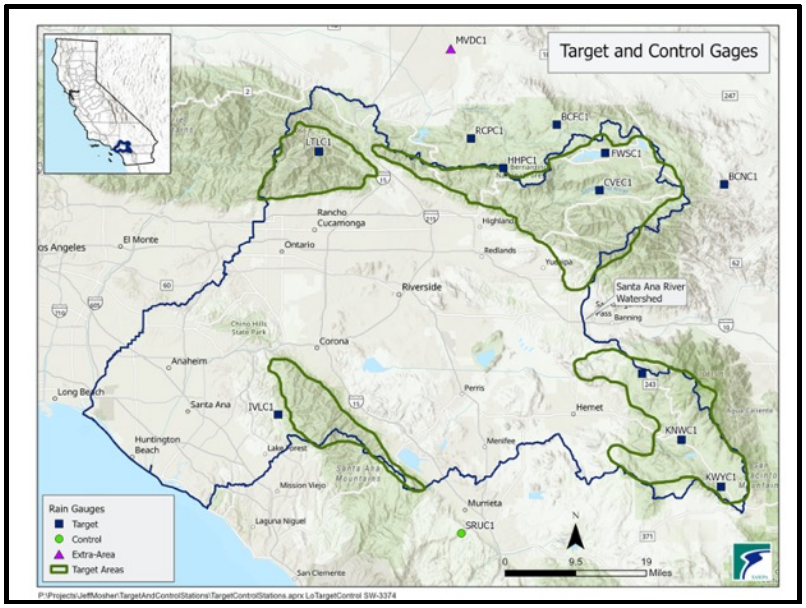


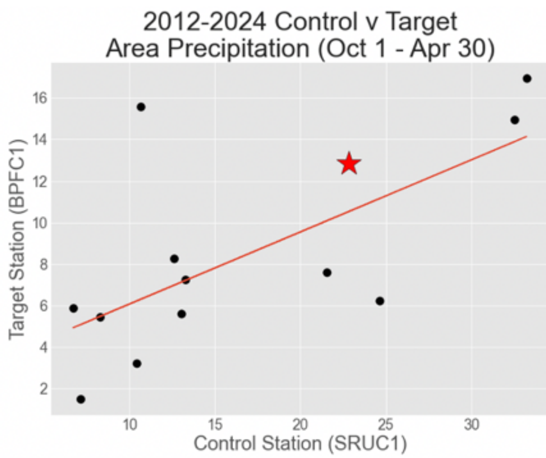
Figure 14: Map showing the greater target and control gauge network locations.

3.5.2 Northeast Area Target-Control Analysis

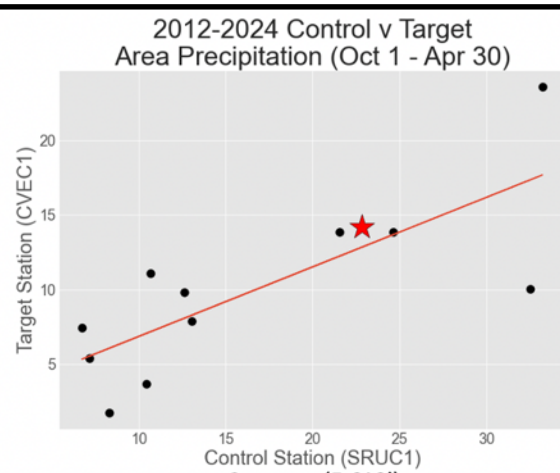
Obtaining enough data within the target area gauge network was limited, so the definition of the Northeastern target area slightly expanded to the north and east to allow enough data to an analysis. All of these areas would have been impacted similarly as the defined target area. Additional stations for analysis are being identified and data quality assurance and control analysis are currently underway.

Figure 15 – Figure 17 show the target control analysis for six gauges identified in the northeast region. Black dots on the plot represent the non-seeded paired yearly total precipitation values. The regression line is shown in red and the seeded WY24 value is shown as a red star.

The results show that all of gauges except Fawnskin (FWSC1) had precipitation values between 10% and 25% above the climatological regression line, potentially suggesting a positive seeding effect.

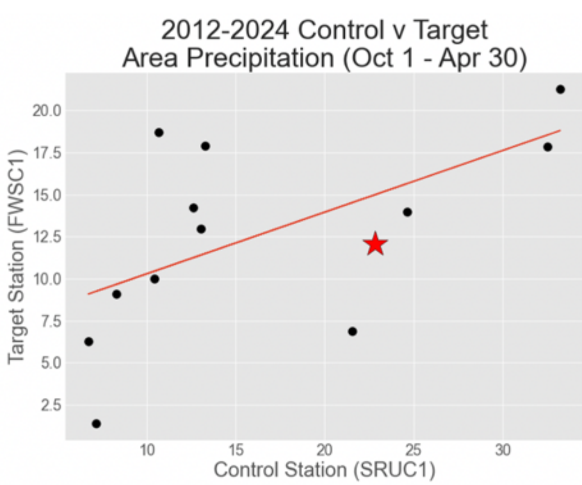


Big Pine Flat (6,851')
V
Santa Rosa Plateau (1,987')
Expected precipitation 10.2" observed 12.8"
(+25.5%)

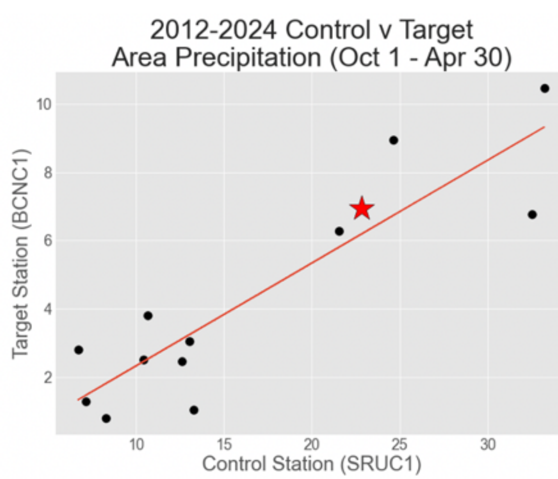


Converse (5,618')
V
Santa Rosa Plateau (1,987')
Expected precipitation 13.0" observed 14.4"
(+10.7%)

Figure 15. Northeast target area Target-Control November 1 – April 30 for Big Pine Flat (left) and Converse (right) vs. the control site Santa Rosa Plateau. Black dots on the plot represent the non-seeded paired yearly total precipitation values. The regression line is shown in red and the seeded WY24 value is shown as a red star.



Fawnskin (6,900')
V
Santa Rosa Plateau (1,987')
Expected precipitation 15.0" observed 12.0"
(-20.0%)



Burns Canyon (6,284')
V
Santa Rosa Plateau (1,987')
Expected precipitation 6.1" observed 6.9"
(+12.1%)

Figure 16: Northeast target area Target-Control November 1 – April 30 for Fawnskin (left) and Burns Canyon (right) vs. the control site Santa Rosa Plateau. Black dots on the plot represent the non-seeded paired yearly total precipitation values. The regression line is shown in red and the seeded WY24 value is shown as a red star.

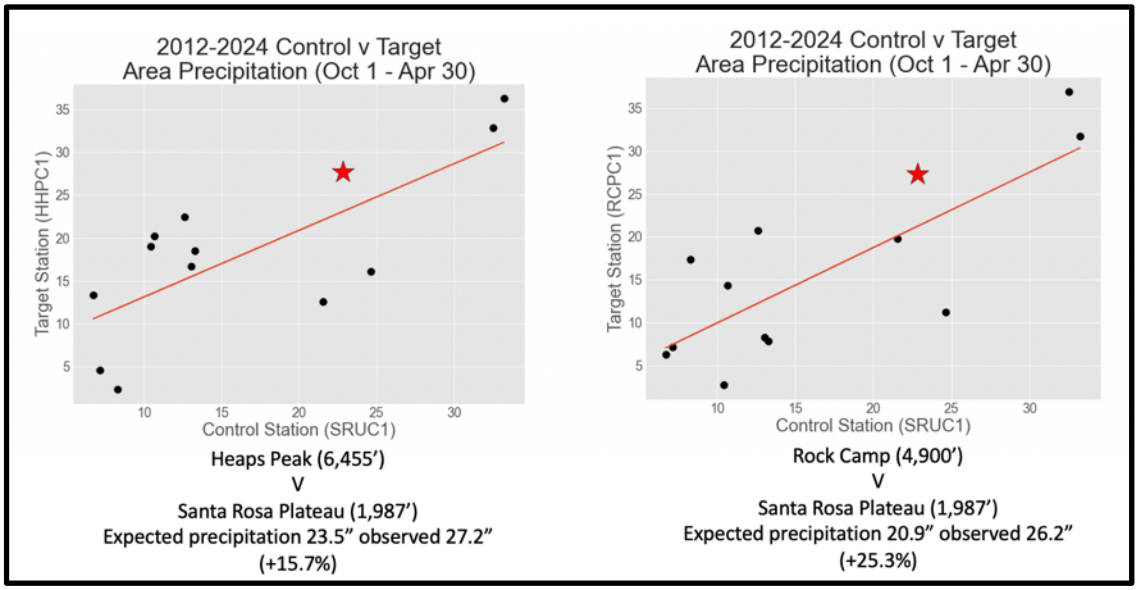


Figure 17: Northeast target area Target-Control November 1 – April 30 for Heaps Peak (left) and Rock Camp (right) vs. the control site Santa Rosa Plateau. Black dots on the plot represent the non-seeded paired yearly total precipitation values. The regression line is shown in red and the seeded WY24 value is shown as a red star.

3.5.3 Northwest Area Target-Control Analysis

Figure 18 show the results of the target-control analysis for the Middle Fork Lytle Creek and the Lytle Creek precipitation gauges compared to the Santa Rosa Plateau gauge. The WY24 relationship showed that Middle Fork Lytle Creek has the expected amount of precipitation and Lytle Creek had less precipitation (-18.5%) than would be expected given the observed value at Santa Rosa Plateau, suggesting no impact from cloud seeding.

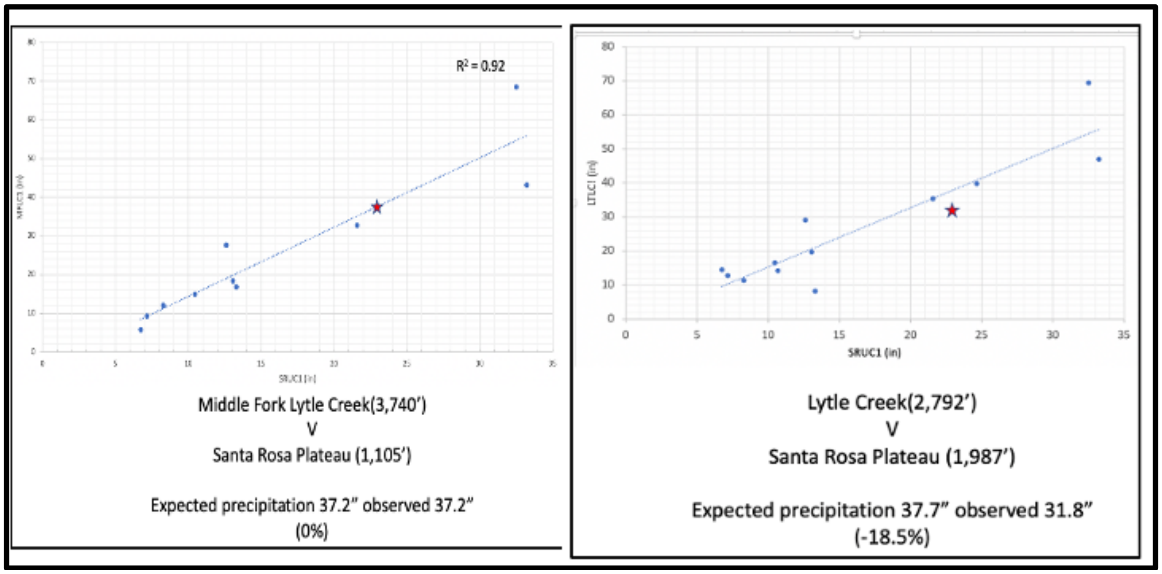


Figure 18: Northwest target area Target-Control November 1 – April 30 for Middle Fork Lytle Creek and Lytle Creek vs. the control site Santa Rosa Plateau. Blue dots on the plot represent the non-seeded paired yearly total precipitation values. The regression line is shown in red and the seeded WY24 value is shown as a red star.

3.5.4 Southeast Area Target-Control Analysis

Figure 19 shows the results of the target-control analysis for the Keenwild, Kenworthy, and Vista. Grande precipitation gauges compared to the Santa Rosa Plateau gauge. The results show that Keenwild and Kenworthy had values very close to the regression line indicating no seeding effect, whereas Vista Grand had 13.9% more precipitation than would be expected given the derived climatological Vista Grand-Santa Rosa Plateau relationship precipitation.

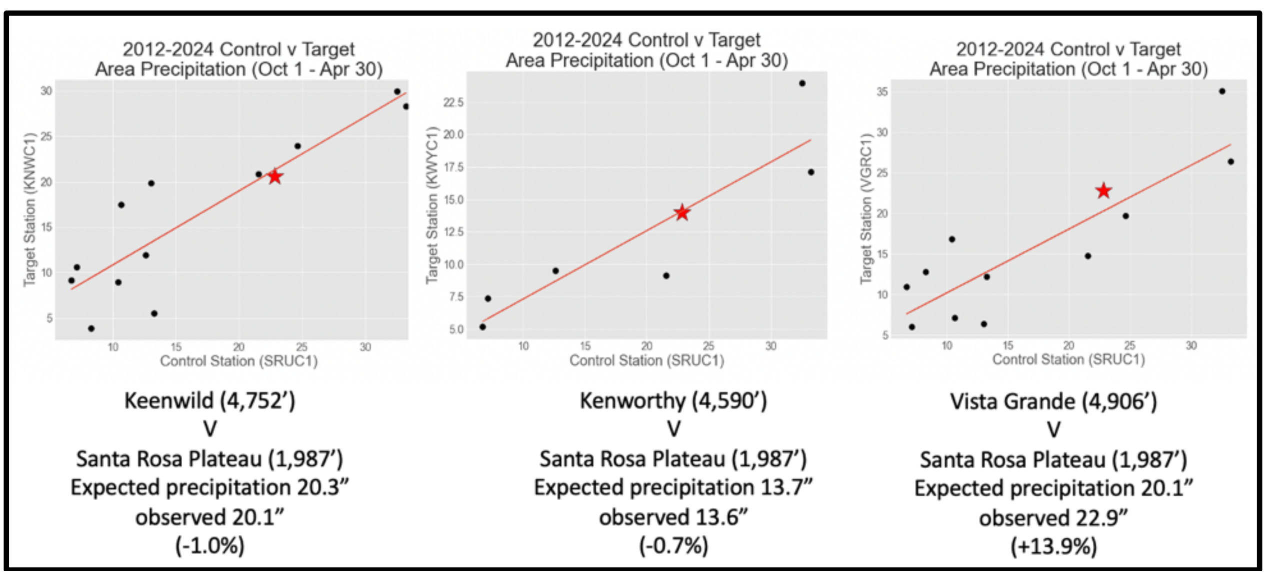


Figure 19: Southeast target area Target-Control November 1 – April 30 for Keenwild (left), Kenworthy (center), and Vista Grande (right) vs. the control site Santa Rosa Plateau. Black dots

on the plot represent the non-seeded paired yearly total precipitation values. The regression line is shown in red and the seeded WY24 value is shown as a red star.

3.5.5 Southwest Area Target-Control Analysis

Figure 20 shows the results of the target-control analysis for the Silverado precipitation gauge compared to the Santa Rosa Plateau gauge. The results show that Silverado had 4.7% less precipitation than would be expected based on the Santa Rosa Plateau regression relationship. This could be due to natural variability and the limited seeding that occurred.

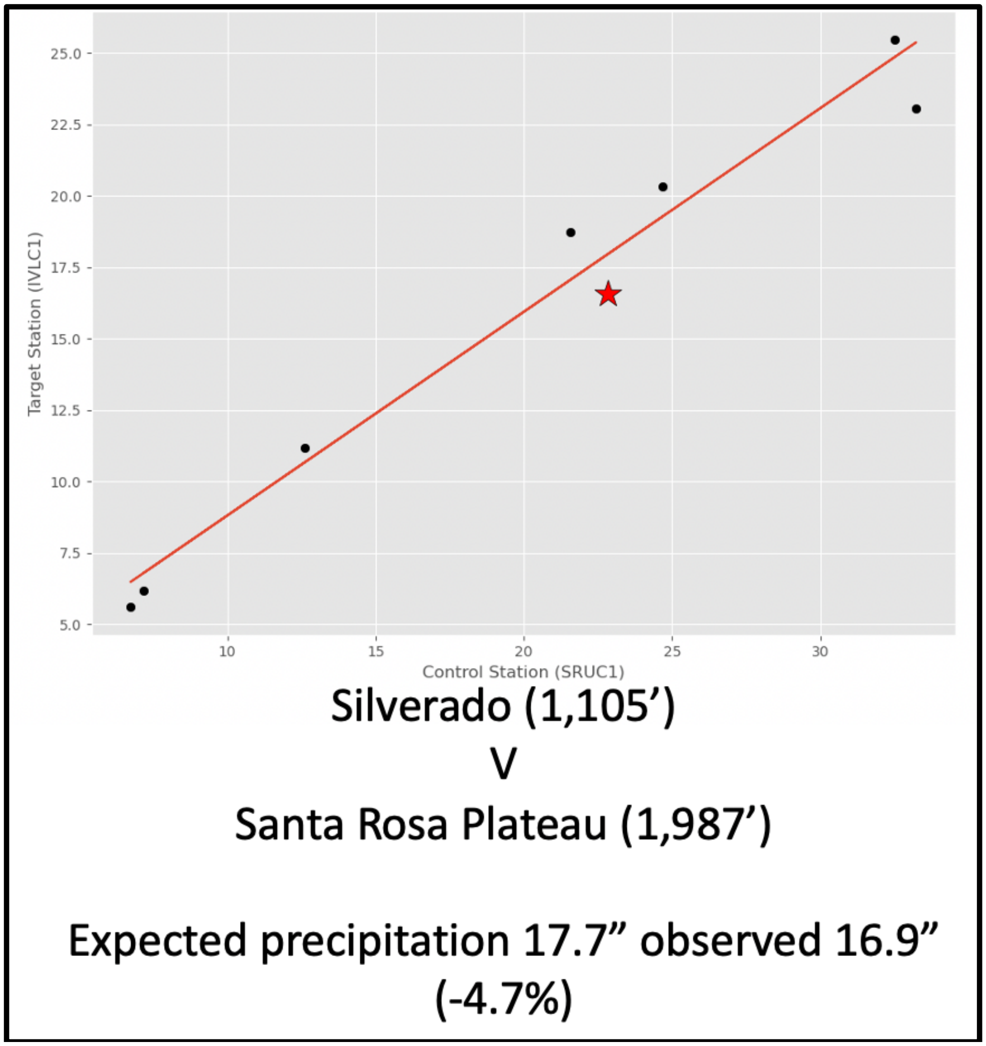


Figure 20: Southwest target area Target-Control November 1 – April 30 for Silverado vs. the control site Santa Rosa Plateau. Black dots on the plot represent the non-seeded paired yearly total precipitation values. The regression line is shown in red and the seeded WY24 value is shown as a red star.

3.5.6 Extra Area Effect Target-Control Analysis

In order to confirm that the cloud seeding project is not decreasing precipitation downwind of the target area, the Mojave Dam seasonal precipitation observations were compared to the Santa Rosa Plateau control gauge. The Mojave Dam site is at the base of the north side of the San Bernardino Mountains, north and downwind of the Santa Ana headwaters. Figure 21 shows the results of this comparison. For WY24 Mojave Dam had 12.9% more precipitation than the long-term climatological relationship would predict.

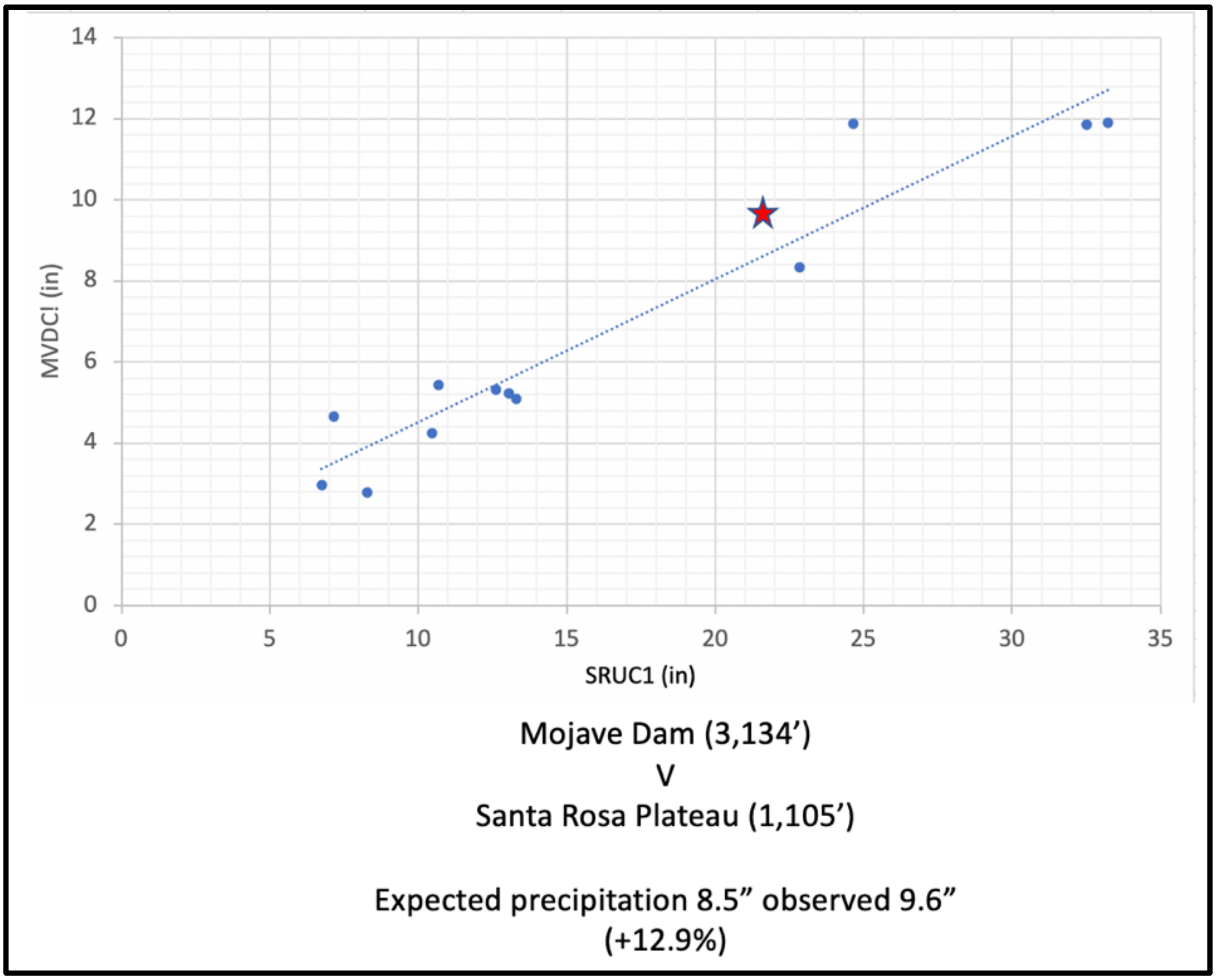


Figure 21: Extra-area Target-Control November 1 – April 30 for Silverado vs. the control site Santa Rosa Plateau. Black dots on the plot represent the non-seeded paired yearly total precipitation values. The regression line is shown in red and the seeded WY24 value is shown as a red star.

3.5.7 Target-Control Results Summary

Positive seasonal seeding precipitation increases were observed for 5 of 6 Northeast target area gauges, and the northern gauge of the Southeast target area. Neutral to negative seasonal precipitation increases were observed over the Northwest (1 gauge) and the Southwest (limited seeding). The extra-area gauge suggested a precipitation increase. More data than one point would be needed to determine statistical significance and therefore substantial conclusions cannot be drawn from this analysis at this time but the trends are positive for this first year.

3.5.8 Target-Control Increases by Target Area

3.5.8.1 Northeast

The mean expected precipitation using the 6 gauges analyzed across the Northeast Target Area yielded a value of 14.78” of expected precipitation. The mean change in precipitation across the 6 gauges is a 12.2%, increase in precipitation of 1.8”. Each generator has a 30 sq mile footprint of seeding impact and there are 6 generators across the target area. The increase in precipitation can be computed as follows:

Total increase = 6 generators X 1.8 in X (1 ft/12 in) X 30 sq miles per generators X (640 acres/1 sq mile)

Total Northeast increase = 17,280 acre-ft

Doing the same analysis with only the 3-gauges that are strictly within the target area (Converse, Fawnskin, and Heaps Peak) yielded a mean of 17.8” of expected precipitation. The mean change in precipitation across the 6 gauges is a 4.1%, an increase in precipitation of 0.7”. The increase in precipitation is computed as follows:

Total increase = 6 generators X 0.7 in X (1 ft/12 in) X 30 sq miles per generators X (640 acres/1 sq mile)

Total Northeast increase = 6,720 acre-ft

The difference between the greater target area and the strict target area results are primarily due to the single Fawnskin (FWSC1) gauge which was significantly lower that the climatological median. The results of the currently underway model plume analysis will help provde insight to why this gauge was so much different than the 5 other gauges analyzed for in the greater target area.

3.5.8.2 Southeast

The mean expected precipitation using the 3 gauges analyzed across the Southeast Target Area yielded values of 18.0”. The mean change in precipitation across the 3 gauges is 4.06%, increase in precipitation of 0.828”. Since each generator has a 30 sq mile footprint in seeding impact and there are 3 generators across the target area. The increase in precipitation can be computed as follows:

Total increase = 3 generators X 0.828 in X (1 ft/12 in) X 30 sq miles per generators X (640 acres/1 sq mile)

Total Southeast increase = 3,974 acre-ft

3.5.8.3 Northwest

Using the two available gauges in the Northwest Target Area the results show less precipitation than expected. Therefore, the were no measured increase in precipitation from cloud seeding was observed.

Total Northwest increase = 0 acre-ft

3.5.8.4 Southwest

Using the only available gauge in the Southwest Target Area the results show less precipitation that expected. Therefore, the were no measured increase in precipitation from cloud seeding.

Total Southwest increase = 0 acre-ft

3.5.8.5 Summary

The total increase in precipitation for each of the target areas is shown in Figure 22. The Northeast target area was by far the most productive. The Southeast target area had a limited number of seeding events but still potentially generated 3,974 acre-ft. Sparse and poor gauge locations made the Northwest analysis difficult, and very limited seeding in the Southwest led to both target areas ending up with negative values.

The total project yield based on the target-control analysis suggested a ***23,175 acre-ft increase*** over what would have fallen. As previously mentioned, additional data will need to be collect over the remainder of the project to confirm these results.

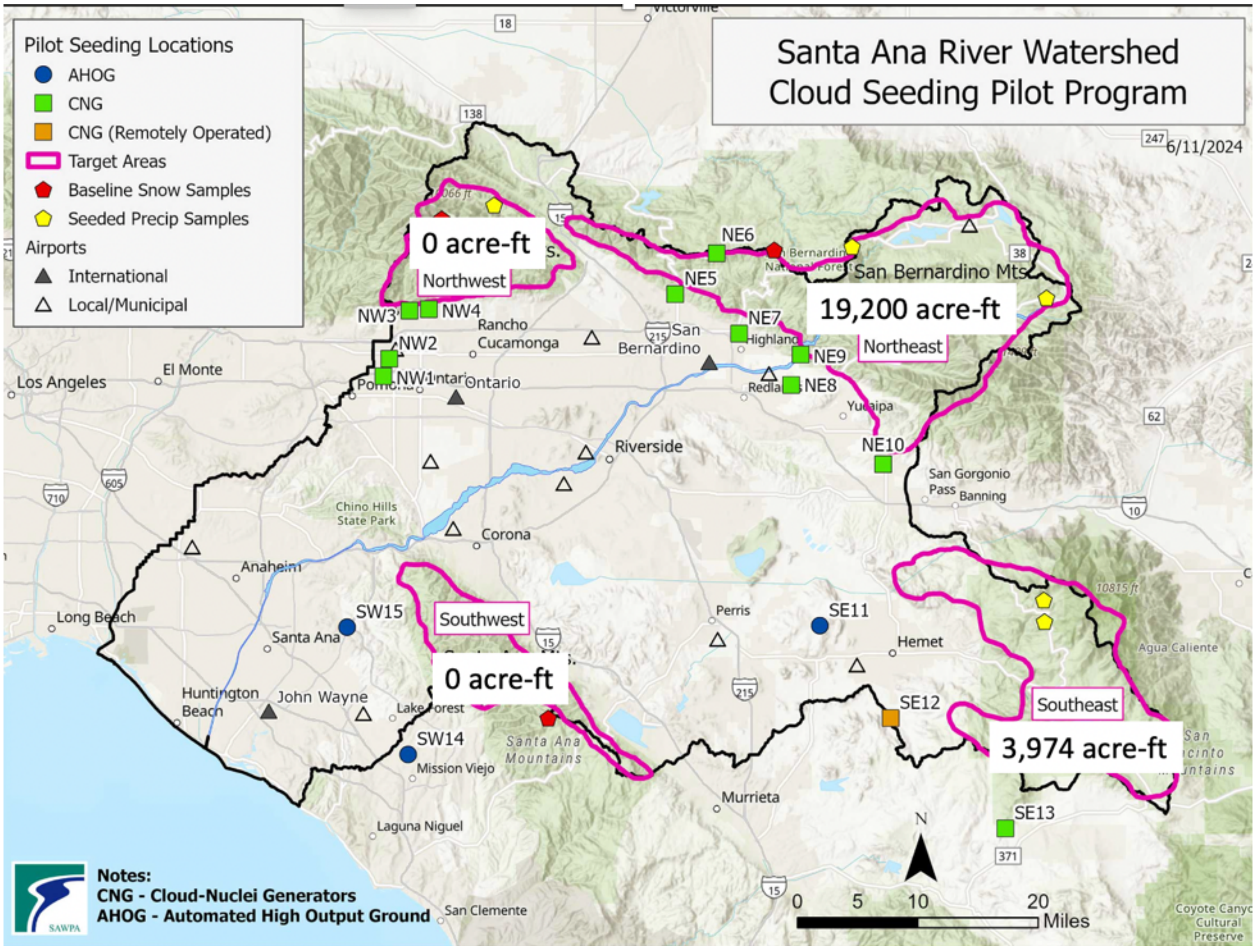


Figure 22: Total estimated cloud seeding increases in precipitation for each target area based on the target-control analysis.

3.6 Task 5. Streamflow Analysis

3.6.1 Overview and Methodology

Similar to the precipitation target and control analysis of Task 4, a runoff target-control analysis was conducted using streamflow gauge data. The best representative United States Geologic Survey (USGS) streamflow gauge from each of the target areas was assessed. Note: a streamflow assessment for the Southwest Target area was not completed due to the very limited seeding done over that area. The best control gauge in the San Gabriel Mountains that didn't have any upstream reservoirs was selected. The total streamflow between December 1 and May 31 was determined to be representative of the winter storm snow and rain runoff. This was done by using the daily streamflow observations and converting it to acre-feet passing the gauge by day. All of the days across Dec 1 – May 31 interval were summed yielding the 6-month streamflow.

The location of the control gauge near the location where the Arroyo Seco River exits the southern slopes of the San Gabriel Mountains is shown in Figure 23. This gauge has no water storage upstream of the gauge and would be representative of storm runoff across the area.

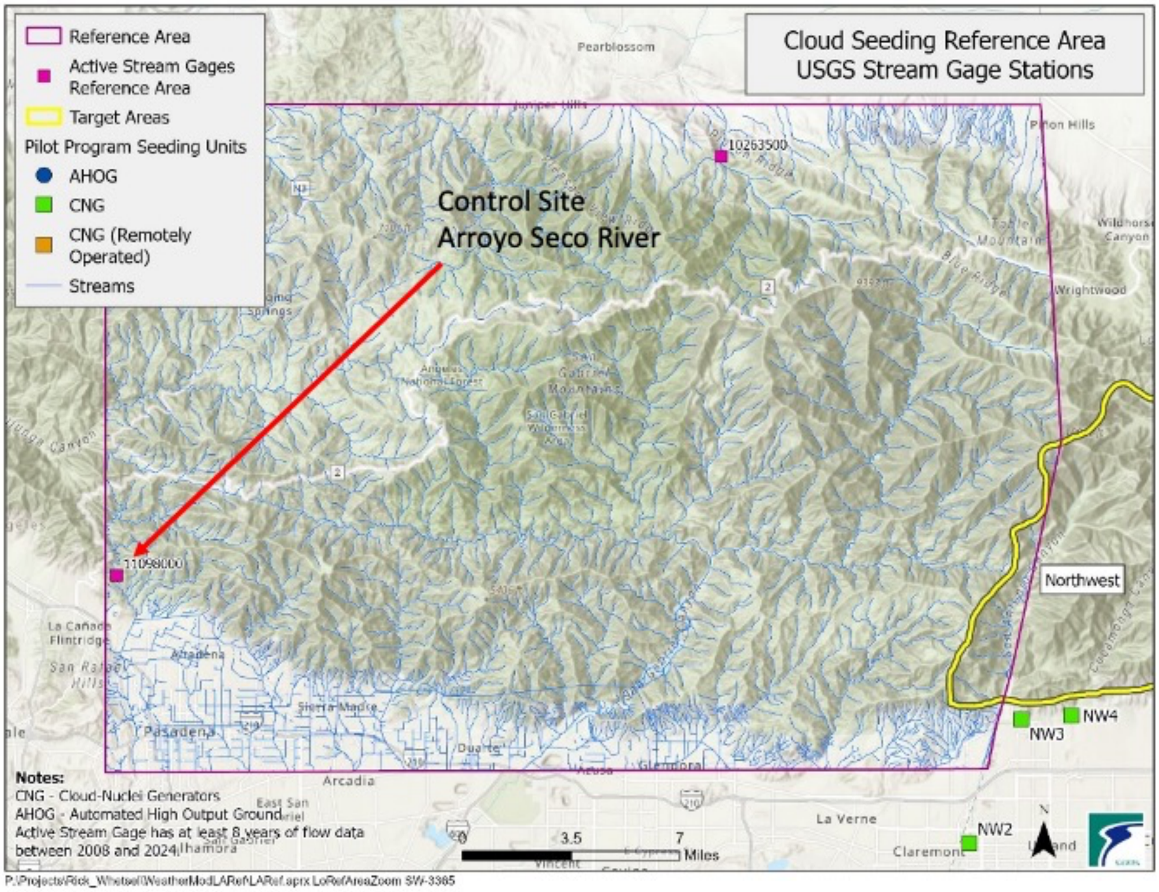


Figure 23:The location of the USGS gauge on the Arroyo Seco River.

The location of the Northeast Target area gauge was the Highlands Near City Center USGS gauge at the location where the Santa Ana River exits the San Bernardino Mountains Figure 24. This gauge measures all of the runoff from the headwaters area of the watershed, Mt Gorgonio, and the Big Bear area. There is some upstream water storage in Big Bear Lake but much of the runoff directly associated with winter storms and spring snowmelt directly passes the gauge.

Figure 24: Northeast Target Area USGS Gauge Highlands Near City Center.

The 15-year comparison between the San Gabriel gauge and the Santa Ana River gauge is shown in Figure 25. The unseeded relationship (black dots) show there is a good relationship between the runoff, with an excellent correlation coefficient of 0.952. There is some spread in the values during the wetter years. The red star shows seeded winter (2023-2024) relationship, at 200 acre-feet more runoff in the Santa Ana River compared to the expected value. This obviously is not enough seeded runoff data to draw a conclusion.

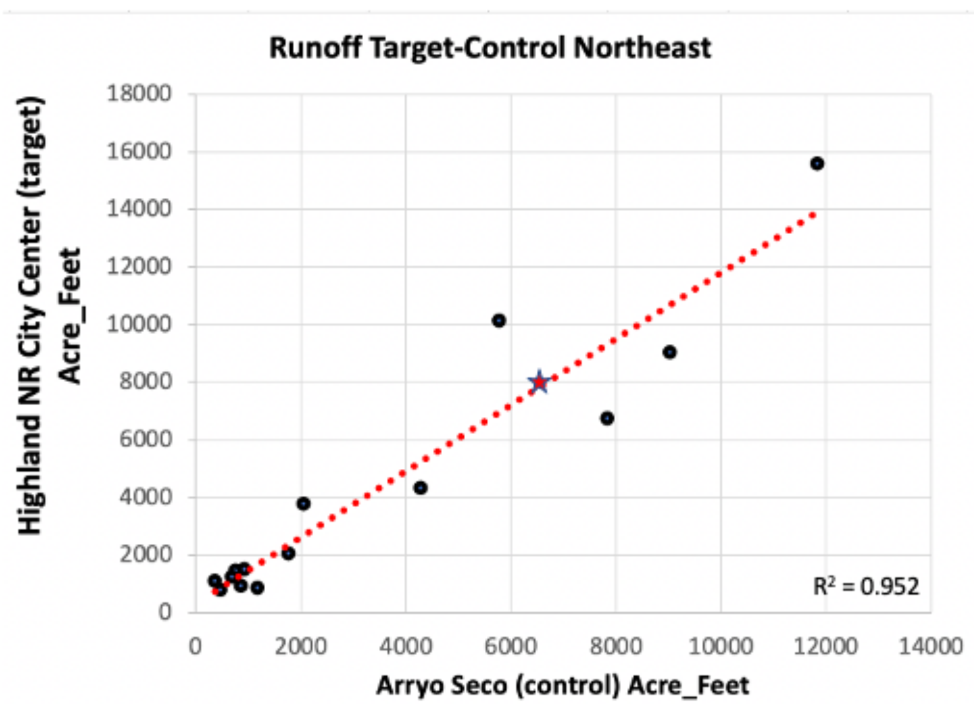


Figure 25: 15-year San Gabriel Control runoff compared to the Northeast Target Area runoff (black dots). The best fit line between the unseeded realtaionship is shown in red and the seeded winter 2023-2024 is shown as a star.

The location of the Northwest Target area gauge was the Lytle Creek Near Fontana USGS gauge at the location where Lytle Creek exits the eastern side of the Mountains (Figure 26). This gauge measures a portion of the runoff from the eastern half of the Northwest Target area. There is no upstream water storage on Lytle Creek.

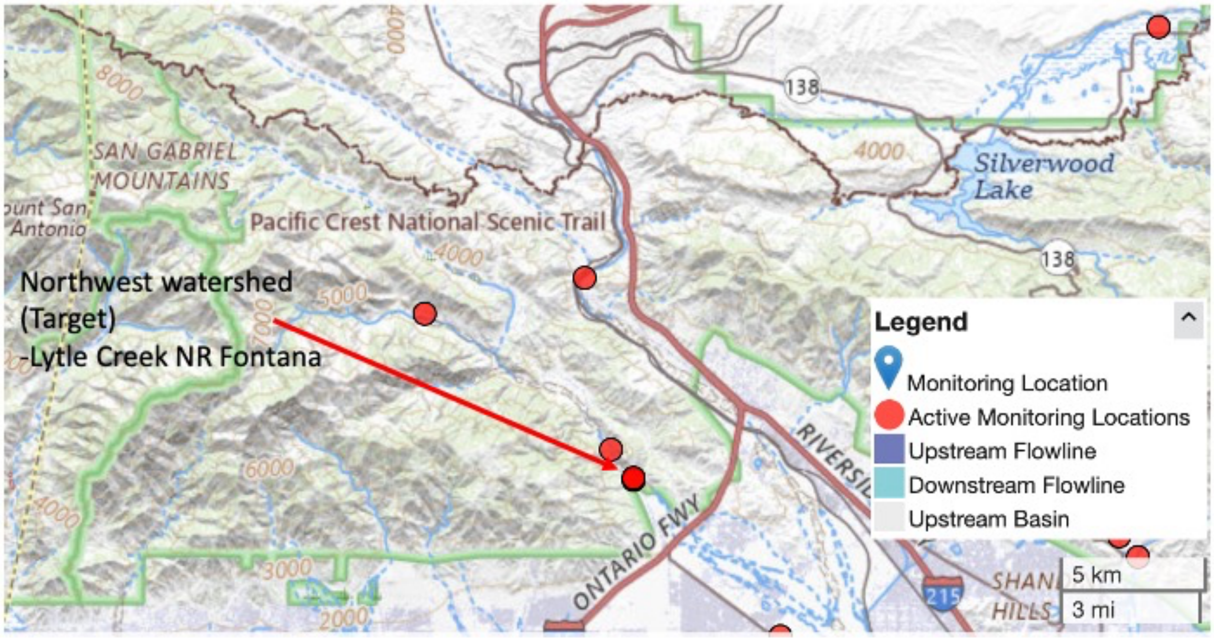


Figure 26: Northwest Target Area USGS Gauge Lytle Creek Near Fontana.

The 15-year comparison between the San Gabriel gauge and the Lytle Creek gauge is shown in Figure 27. The unseeded relationship (black dots) show there is a good relationship between the runoff, with an excellent correlation coefficient of 0.948. The red star shows seeded winter (2023-2024) relationship, about 200 acre-feet less runoff, was observed on the Lytle Creek compared to the expected value from the climatological relationship. This obviously is not enough seeded runoff data to draw a conclusion.

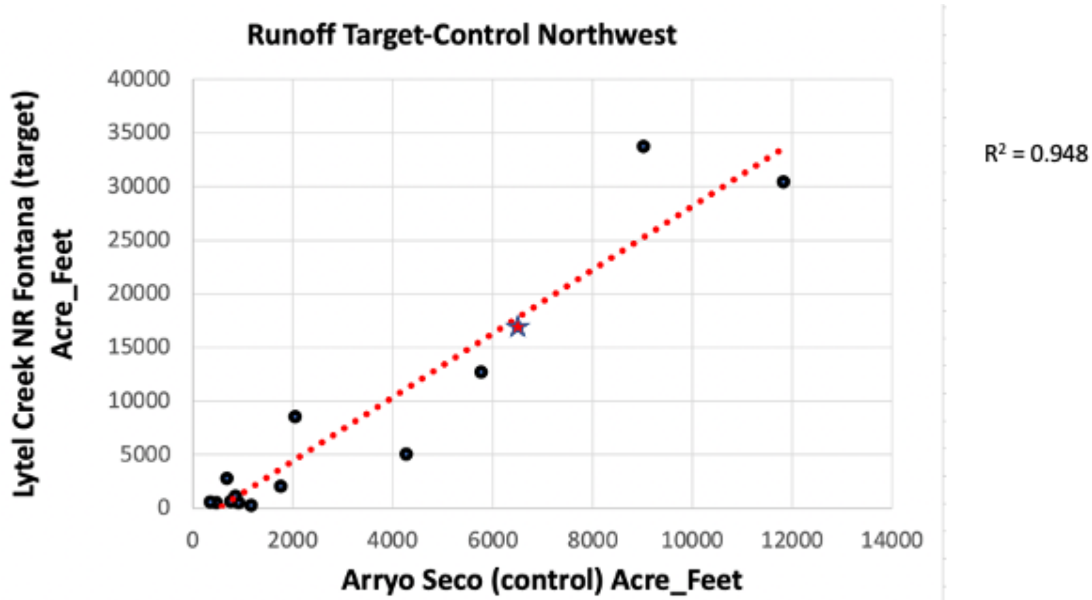


Figure 27: 15-year San Gabriel Control runoff compared to the Northwest Target Area runoff (black dots). The best fit line between the unseeded relationship is shown in red and the seeded winter 2023-2024 is shown as a star.

The location of the Southeast Target area gauge was the San Jacinto Near San Jacinto USGS gauge at the location where the North Fork and South Fork of the San Jacinto meet (Figure 28). The North Fork exits the at the base of the southwestern side of the San Jacinto Mountains and the South Fork moves northwest from the southern end of the range. This gauge measures most of the runoff from the Southeast Target area. Unfortunately, there is an upstream water reservoir on the South Fork, Lake Hemet, that may slightly dampen the cloud seeding signature on runoff. But the high correlation coefficient gives good confidence that this gauge captures the runoff from the target area.

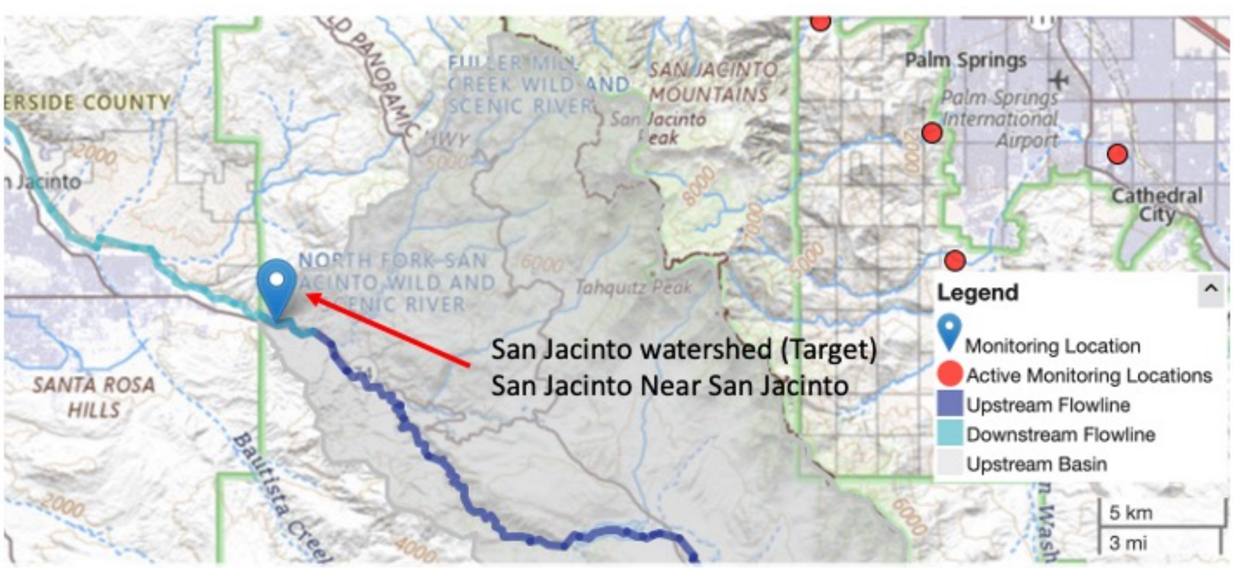


Figure 28: Southeast Target Area USGS Gauge San Jacinto Near San Jacinto.

The 15-year comparison between the San Gabriel gauge and the San Jacinto gauge is shown in Figure 29. Even with the upstream reservoir, the unseeded relationship (black dots) show there is a very good relationship between the runoff, with a correlation coefficient of 0.953. The red star shows the seeded winter (2023-2024) relationship, about 5,000 acre-feet less runoff, was observed at the gauge compared to the expected value from the climatological relationship. This obviously is not enough seeded runoff data to draw a conclusion and could be due to reservoir operations skewing either the climatological relationship or the seeded year relationship. In addition, there were several years in the climatology that Arroyo Seco had some (low) runoff and San Jacinto had none. This also could skew the climatological relationship.

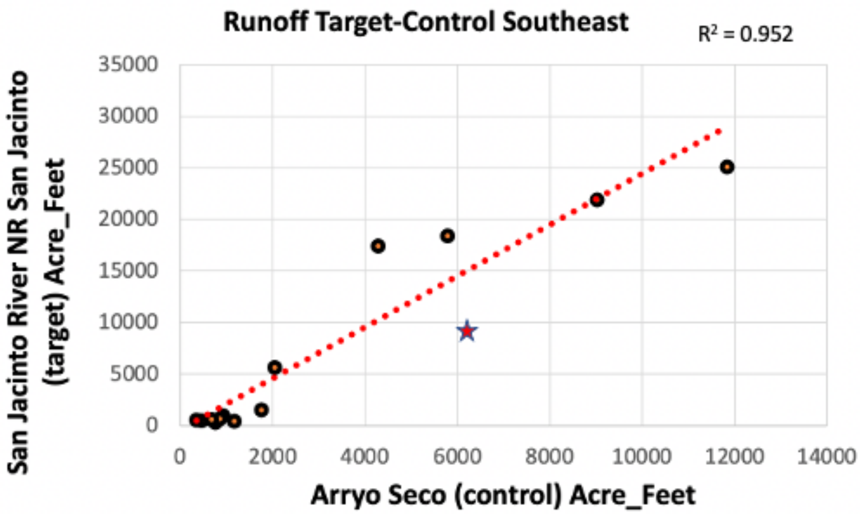


Figure 29: 15-year San Gabriel Control runoff compared to the Southeast Target Area runoff (black dots). The best fit line between the unseeded relationship is shown in red and the seeded winter 2023-2024 is shown as a star.

3.6.2 Runoff Target-Control Summary

An unseeded climatological relationship was created for a control streamflow gauge in the central San Gabriel Mountains and gauges in the Northwest, Northeast, and Southeast target areas. The Southwest did not have enough seeding for this analysis to be attempted. The best gauges that captured the majority of the runoff were chosen in each target area.

The results for year 1 a showed slight increase in runoff for the Northeast target area compared to the unseeded climatological estimate. Big Bear Lake does have a dam so the runoff data is not exactly tied to total seasonal watershed runoff. Runoff on the east side of the Northwest target area were slightly below unseeded climatological estimate. The Southeast target area had a limited number of seeding events and also has a reservoir upstream, making the results more uncertain. The amount of water passing the gauge was about 10% below the expected value. Obviously, the streamflow target and control analysis needs several additional seeded years for the data to become statistically meaningful.

4 Validation Recommendations for Future Years

- Task 1 provided significant insight into the winter storms crossing the area and should continue to be done following each winter.
- The snow chemistry suggested that silver was absent in most of the samples. This suggests that the (AgI) cloud seeding ice nuclei are not reaching the collection locations. This may be due to the plumes just missing the collection locations, although Hysplit plume modeling suggests the collection locations were well placed to intercept the seeding plume. We recommend a significantly larger collection effort in the next seeded year.
- The one outstanding question in assessing the cloud seeding success is determining whether the cloud seeding plumes are rising from the generator locations to the -5°C altitude in a short enough time to create Santa Ana Basin precipitation. The free Hysplit plume model suggests that the cloud seeding plumes sometimes don't reach the -5°C level in time for successful seeding. DRI high-resolution modeling and associated plume modeling is much better than the free Hysplit model. We recommend doing a few case studies using this modeling package to confirm successful vertical mixing. (This analysis it currently underway).
- Due to the uncertainty of the success of vertical mixing of the low altitude generated seeding plumes to the -5°C level of the atmosphere, and the fact that the aircraft can fly at the seedable altitudes and directly seed the clouds upstream of the target area, aircraft seeding should be looked into.
- Continue to improve the streamflow accounting by working to obtain time-series reservoir level data.

5 References

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6 Appendix A

Detailed review of winter weather and independent assessment of cloud seeding operations for task 1.

6.1 Review of NAWC Cloud Seeding Operations

The project started on November 15, 2023. There was only one seeding event during November. (Table A 1) The event, described as a test run, was conducted over the northwest target area. No precipitation was produced during this event. Since this was a test run it was not included in the analysis.

Table A 1: Summary of individual generator operations for November 17, 18 2023 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
17-18-Nov	NW3	18/0045	18/1200	11.25	90	1.41
	NW4	17/2330	18/1245	13.25	106	1.66

In December 2023 there were two seeding events. The first storm occurred on December 21 and 22 (Table A 2). All of the generators except SE12 were started at between 1600 (all times PST) and 2000 local time December 21, 2023 and run through 1600 on December 22, 2023. The potential clouds associated with seeding conditions did not move into the area until 400 on December 22, 2023, approximately 10 hours after storm moved into the area. This was expected due to the requirement that the manual generators need to be started and halted at approximately business hours. Temperatures at 10,000' MSL (700mb) during the seedable portion of the storm cooled from -3^{o}C to -4^{o}C.

Table A 2: Summary of individual generator operations for December 21-22, 2023 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
21-22-Dec	NW3	21/1815	22/1615	22.00	176	2.75
	NW4	21/1845	22/1530	20.75	166	2.59
	NE5	21/1630	22/1900	26.50	212	3.31
	NE6	21/1900	22/1630	21.50	172	2.69
	NE7	21/2045	22/1930	22.75	182	2.84
	NE8	21/1615	22/1430	22.25	178	2.78
	NE9	21/1545	22/1445	23.00	184	2.88
	NE10	21/2015	22/2030	24.25	194	3.03
	SE12	22/0030	22/0915	8.75	70	1.09
	SE13	21/1830	22/1330	19.00	152	2.38

The second storm of the month occurred on December 29 and 30, 2023 (Table A 3). Generators in the Northwest, Northeast, were started on December 29, 2023 between 1615 and 1945. The Southeast generators were started at 600 – 700 on December 30, 2023. The seeding conditions didn't arrive in any of the areas until 0600 on Dec 30, 2023. This was nearly 12 hours after the Northwest and Northeast generators were started. Seeding successfully continued until 1900 During the seeding period winds were favorable and temperatures at 10,000' MSL cooled from -5^{o}C to -6^{o}C.

Table A 3: Summary of individual generator operations for December 29-30, 2023 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
29-30-Dec	NW1	29/1630	30/1530	23.00	184	2.88
	NW2	29/1615	30/1515	23.00	184	2.88
	NW3	29/1715	30/1415	21.00	168	2.63
	NW4	29/1645	30/1445	22.00	176	2.75
	NE5	29/1845	30/1600	21.25	170	2.66
	NE6	30/0530	30/1430	9.00	72	1.13
	NE7	29/1915	30/1615	21.00	168	2.63
	NE8	29/1800	30/1245	18.75	150	2.34
	NE9	29/1815	30/1300	18.75	150	2.34
	NE10	29/1945	30/1700	21.25	170	2.66
	SE12	30/0700	30/1230	5.50	44	0.69
	SE13	30/0600	30/1230	6.50	52	0.81

During January 2024 there were three storm periods. The first storm occurred on January 3, 2024 (Table A 4). Generators from the Northwest, Northeast, and Southeast were all operated for this storm. The generators were started between 0530 and 0730 on January 3, 2024 and halted between 1215 and 1745. Seeding conditions were present across the Southeast through the period. Across the Northeast and Northwest seeding conditions were present after about 1100 with about 5 hours of seeding prior to any precipitation falling at the sampled gauges. Temperatures across the area at 10,000' MSL ranged from -6^{o}C to -10^{o}C.

Table A 4: Summary of individual generator operations for January 3, 2024 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
Jan 03	NW1	0545	1215	6.50	52	0.81
	NW2	0530	1230	7.00	56	0.88
	NW3	0630	1215	5.75	46	0.72
	NE5	0730	1615	8.75	70	1.09
	NE6	0515	1730	12.25	98	1.53
	NE7	0745	1645	9.00	72	1.13
	NE8	0600	1545	9.75	78	1.22
	NE9	0630	1600	9.50	76	1.19
	NE10	0830	1745	9.25	74	1.16
	SE12	0630	1615	9.75	78	1.22
	SE13	0600	1400	8.00	64	1.00

The second storm of the month occurred on January 20, 2024. Generators from the Northeast and Southeast were operated for this storm (Table A 5). The generators were started between 1345 and 1730 on January 20, 2024 and halted in the morning of January 21, 2024 between 0815 and 1015. Favorable cloud and wind conditions for seeding were present across the Northeast through the operations period. Favorable conditions were also present across the Southeast target area during the seeding storm period. Temperatures cooled from -3^{o}C to -5^{o}C through the storm period.

Table A 5: Summary of individual generator operations for January 20-21, 2024 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
Jan 20-21	NE5	20/1600	21/0915	17.25	138	2.16
	NE6	20/1515	21/0815	17.00	136	2.13
	NE7	20/1630	21/0930	17.00	136	2.13
	NE8	20/1345	21/0815	18.50	148	2.31
	NE9	20/1415	21/0830	18.25	146	2.28
	NE10	20/1730	21/1015	17.75	142	2.22
	SE13	20/1700	21/0815	15.25	122	1.91

The third storm of the month quickly followed the second storm, with seeding operations occurring between 0630 on January 21, 2024 through 0800 on January 22, 2024. Seeding was again only conducted in the Northeast and Southeast target areas (Table A 6). Seeding conditions didn't arrive in the Northeast and Southeast target area until 0500 on January 22, 2024, approximately 10 hours after the generators were started. As previously mentioned, this was expected due to the requirement that the manual generators need to be started by hand at approximately business hours. The period between 0500 and 2000 on January 22 had low clouds and favorable moisture. Temperatures through the seeded period were about -3^{o}C.

Table A 6: Summary of individual generator operations for January 21-22, 2024 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
Jan 21-22	NE5	21/1830	22/1900	24.50	196	3.06
	NE6	22/0500	22/1915	14.25	114	1.78
	NE8	21/1900	22/1815	23.25	186	2.91
	NE9	21/1915	22/1830	23.25	186	2.91
	NE10	21/1915	22/2000	24.75	198	3.09
	SE13	21/1915	22/1945	24.50	196	3.06

There were 2 seeded storms in February and a series of atmospheric river storms between February 4, 2024 and February 8, 2024 which was not seeded due to very heavy precipitation and the associated flood threat.

The first seeded storm occurred on February 1, 2024 (Table A 7). The Northwest, Northeast, and Southeast target areas were all seeded during this storm. The NW2 and NW3 generators were started the evening before the event. Over the Northwest, Northeast, and Southeast target areas seedable conditions arrived just before 0500 on February 1, 2024 and continued until 1700. All of the generators (except NW3 and NW4) were started and halted at the correct times. The temperatures at 10,000' MSL cooled from -3^{o}C to -6^{o}C during the seeded period.

Table A 7: Summary of individual generator operations for February 1, 2024 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
Jan 31-Feb 01	NW1	01/0645	01/1645	10.00	80	1.25
	NW2	01/0715	01/1615	9.00	72	1.13
	NW3	31/1730	01/1700	23.50	188	2.94
	NW4	31/1715	01/1615	23.00	184	2.88
	NE6	01/0515	01/1700	11.75	94	1.47
	NE8	01/0700	01/1445	7.75	62	0.97
	NE9	01/0715	01/1515	8.00	64	1.00
	NE10	01/0730	01/1900	11.50	92	1.44
	SE12	01/0415	01/1815	14.00	112	1.75
	SE13	01/0615	01/1830	12.25	98	1.53

The second potentially seedable storm moved into the area during the afternoon of February 20, 2024. (Table A 8) The generators targeting the Northeast and Northwest target areas were activated between 1315 and 1745 and halted the morning of February 21, 2024 between 0945 and 1345. Favorable clouds and winds were present during this entire time period. Temperatures cooled from -4ºC to -5ºC during the seeding period.

Table A 8: Summary of individual generator operations for February 20-21, 2024 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
Feb 20-21	NW1	20/1715	21/1000	16.75	134	2.09
	NW2	20/1745	21/1000	16.25	130	2.03
	NW3	20/1600	21/1130	19.50	156	2.44
	NW4	20/1630	21/1215	19.75	158	2.47
	NE6	20/1530	21/0945	18.25	146	2.28
	NE7	20/1445	21/1345	23.00	184	2.88
	NE9	20/1315	21/0945	20.50	164	2.56
	NE10	20/1415	21/1430	24.25	194	3.03

There were three potentially seedable storms during the month of March 2024. The first storm arrived on March 6, 2024 (Table A 9). The Northeast, Northwest, and Southeast were all started between about 1415 on March 6, 2024 and 1000 on March 7, 2024. Seeding times matched the best moisture. But precipitation increases were marginal across the Northwest and Northeast. Nearly a third of an inch of precipitation was measured over the Southeast target area. Seeding conditions over the Northwest and Northeast were marginal with better conditions over the Southeast.

Table A 9: Summary of individual generator operations for March 6-7, 2024 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
Mar 06-07	NW1	06/1700	07/0900	16.00	128	2.00
	NW3	06/1730	07/0730	14.00	112	1.75
	NW4	06/1700	07/0700	14.00	112	1.75
	NE5	06/1545	07/0845	17.00	136	2.13
	NE6	06/1500	07/0500	14.00	112	1.75
	NE7	06/1515	07/0900	17.75	142	2.22
	NE8	06/1430	07/0530	15.00	120	1.88
	NE10	06/1445	07/1000	18.75	150	2.34
	SE12	06/1415	07/0715	17.00	136	2.13
	SE13	06/1715	07/0600	12.75	102	1.59

The second seedable storm of the month occurred on March 23-24, 2024 (Table A 10). The Northwest, Northeast, and Southeast target area were all seeded. Seeding was started between 1215 and 1515 on March 23, 2024 and ended on March 24 between 0830 and 1115. The seeding start times were correct, but precipitation and successful seeding ended over the Northwest and Northeast target areas at 0100 on March 24, 2024. Over the Southeast target area seeding conditions were present from 0200 on March 23, 2023 to 1900 then again between midnight March 24, 2024 and 0900 March 24 when winds clearly became northwesterly. Temperatures at 10,000' MSL were between -6ºC and -10ºC.

Table A 10: Summary of individual generator operations for March 23-24, 2024 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
Mar 23-24	NW1	23/1315	24/1115	22.00	176	2.75
	NW2	23/1345	24/1000	20.25	162	2.53
	NW3	23/1245	24/1115	22.50	180	2.81
	NW4	23/1215	24/1045	22.50	180	2.81
	NE5	23/1345	24/1230	22.75	182	2.84
	NE6	23/1430	24/0830	18.00	144	2.25
	NE7	23/1415	24/1300	22.75	182	2.84
	NE8	23/1215	24/0845	20.50	164	2.56
	NE9	23/1230	24/0845	20.25	162	2.53
	NE10	23/1515	24/1345	22.50	180	2.81
	SE12	23/1400	23/1845	4.75	38	0.59
	SE13	23/1415	24/0830	18.25	146	2.28

The seeding from the final storm of the month started between 0700 and 1145 on March 30, 2024 and was halted on March 31, 2024 between1400 and 1700 (Table A 11). Seeding was conducted in the Northeast, Northwest, and Southeast project areas, with 2 flares burned over the Southwest, and the one over the Southeast. Seeding conditions were generally present throughout the period across the Northwest, Northeast, and Southeast target areas. The flares were also burned during seedable periods. Temperatures at 10,000' MSL during this storm ranged from -6ºC to -8ºC.

Table A 11: Summary of individual generator operations for March 30-31, 2024 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
Mar 30-31	NW1	30/0800	31/1400	30.00	240	3.75
	NW3	30/1145	31/1430	26.75	214	3.34
	NW4	30/1115	31/1500	27.75	222	3.47
	NE5	30/0845	31/1600	31.25	250	3.91
	NE6	30/0745	31/1500	31.25	250	3.91
	NE7	30/0915	31/1630	31.25	250	3.91
	NE9	30/0700	31/1515	32.25	258	4.03
	NE10	30/0945	31/1700	31.25	250	3.91
	SE12	30/0530	31/1430	33.00	264	4.13
	SE13	30/0615	31/1500	32.75	262	4.09

The month of April had two seeding events. The first occurred on April 5, 2024 starting between 0630 and 1000 and ending between 1545 and 0845 (Table A 12). Seeding was conducted in the Northwest, Northeast, and Southeast target areas. Seeding conditions were present through the period although only moderate precipitation increases were realized. Temperatures at 10,000' MSL were cold starting at -10ºC and cooling to -12ºC.

Table A 12: Summary of individual generator operations for April 5, 2024 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
Apr 05	NW1	0630	1915	12.75	102	1.59
	NW2	0630	1545	9.25	74	1.16
	NW3	0930	1800	8.50	68	1.06
	NW4	0945	1815	8.50	68	1.06
	NE5	0730	1945	12.25	98	1.53
	NE6	0615	2015	14.00	112	1.75
	NE7	0745	2015	12.50	100	1.56
	NE8	0645	1945	13.00	104	1.63
	NE9	0645	1930	12.75	102	1.59
	NE10	0830	2045	12.25	98	1.53
	SE12	1000	1900	9.00	72	1.13
	SE13	0615	1900	12.75	102	1.59

The final storm of the season occurred on April 13 – 14, 2024 (Table A 13). Seeding was conducted in the Northeast, Northwest, and Southeast target areas. The generators were turned on at most sites on April 13, 2024 between 1700 and 2015. With three generators started at noon on April 14. The generators were halted on April 14, 2024 between 1815 and 2130. Over the Northwest seeding conditions were present between 1700 on April 13, 2024 and midnight April 14, and again between 1700 and 2015. Over the Northeast, seeding conditions were present between 2100 April 13 and 0700 April 14, and again between 1700 and 2100. Across the Southeast, conditions were present between 1700 on April 13, 2024 and midnight April 14, and again between 1300 and 2100.

Table A 13: Summary of individual generator operations for April 13-14, 2024 (from NWWC final report)

Date	Location	Time on	Time off	Total Hours	AgI (g)	Acetone (gal)
Apr 13-14	NW1	14/1200	14/1900	7.00	56	0.88
	NW2	14/1230	14/1930	7.00	56	0.88
	NW3	13/1745	14/1830	24.75	198	3.09
	NW4	13/1815	14/1915	25.00	200	3.13
	NE5	13/1845	14/2015	25.50	204	3.19
	NE6	13/1745	14/0600	12.25	98	1.53
	NE6	14/1245	14/2045	8.00	64	1.00
	NE7	13/1915	14/2045	25.50	204	3.19
	NE8	13/1715	14/1815	25.00	200	3.13
	NE9	13/1700	14/2130	25.50	204	3.19
	NE10	13/2015	14/2130	25.25	202	3.16

6.2 Notes on the seeding events.

November 2024
- There were no missed seedable periods.
  - One seedable storm: November 17-18, 2023.
    - Only NW3 and NW4 were operated (turned on at midnight and off at noon on Nov 18)
    - No precipitation during seeding period at Lytle Creek
    - 10,000’ MSL temperatures -3C (too warm?)
    - Stabilty ok, not great
    - No additional precip.

- There were no missed seedable periods.
  - December 21-22, 2023.
    - NW, NE, and SE generators were operated (turned on at about 5PM on Dec 21 and off at about 3PM on Dec 22)
    - 0.51” of precipitation fell during the seeding period at Lytle Creek
    - 0.56” of precipitation fell during the seeding period at Angelus Oaks
    - 10,000’ MSL temperatures -3C (too warm?)

    - Stability ok, not great
    - Winds became northeasterly at 100 on Dec 22, seeding should have been halted at that time.
    - NE (7 hours X 0.02 X
  - December 29-30, 2023.
    - NW, NE, and SE generators were operated (turned on at about 5PM on Dec 29 and off at about 3PM on Dec 30)
    - 0.38” of precipitation fell during the seeding period at Lytle Creek
    - 0.31” of precipitation fell during the seeding period at Angelus Oaks
    - 10,000’ MSL temperatures -3C (too warm?)
    - Stability ok, not great
    - Weak moisture prior to 400 Dec 30, had 11 hours of runtime prior to event starting
- There were no missed seedable periods.
  - January 3, 2024.
    - NW, NE, and SE generators were operated (turned on at about 630AM on Jan 3 and off at about 2PM on Jan 3)
    - 0.39” of precipitation fell during the seeding period at Lytle Creek
    - 0.05” of precipitation fell during the seeding period at Angelus Oaks
    - 10,000’ MSL temperatures -6C
    - Stability ok
    - Winds SW good.
- There were no missed seedable periods, outside planned shutdown of big atmospheric river storm with potential flooding.
  - January 31 – February 1, 2024.
    - NW, NE, and SE generators were operated (turned on at about 600AM on Feb 1 and off at about 5PM on Feb 1)
    - 1.17” of precipitation fell during the seeding period at Lytle Creek
    - 1.25” of precipitation fell during the seeding period at Angelus Oaks
    - 10,000’ MSL temperatures -4C to -6C
    - Stability ok
    - Winds SSW good.
    - NW3 and NW4 could have been started in the morning of Feb 1, 12 hours later.
  - Feb 20-21, 2024.
    - NW, and NE generators were operated (turned on at about 300PM on Feb 20 and off at about 11AM on Feb 21)
    - 0.92” of precipitation fell during the seeding period at Angelus Oaks
    - 10,000’ MSL temperatures -5.5C good
    - Stability ok,
    - Winds good
- There were no missed seedable periods.
  - March 6-7, 2024.
    - NW, NE, and SE generators were operated (turned on at about 300PM on Mar 6 and off at about 730AM on Mar 7)
    - 0.41” of precipitation fell during the seeding period at James Preserve (SE Target Area)

    - 10,000’ MSL temperatures -6C
    - Stability ok
    - Winds SW good.
  - March 23-24, 2024.
    - NW, NE, and SE generators were operated (turned on at about 1200PM on Mar 23 and off at about 10AM on Mar 24)
    - 0.40” of precipitation fell during the seeding period at Angelus Oaks
    - 10,000’ MSL temperatures -4C (marginal)
    - Stability ok,
    - Good Case
  - March 30-31, 2024.
    - NW, NE, and SE generators were operated (turned on at about 800AM on March 30 and off at about 300PM on Mar 30)
    - 1.77” of precipitation fell during the seeding period at Lytle Creek
    - 10,000’ MSL temperatures -7C
    - Stability, good
    - Winds SW good
    - Cloud base heights at Big Bear below 10,000 MSL.
- There were no missed seeable periods.
  - April 5, 2024.
    - NW, NE, and SE generators were operated (turned on at about 700AM on Apr 5 and off at about 700PM on Apr 5)
    - 0.44” of precipitation fell during the seeding period at Lytle Creek
    - 10,000’ MSL temperatures -10C (great)
    - Stability ok
    - Winds SW good.
    - Cloud bases below 10,000’ MSL at Big Bear
    - Good Case
  - Apr 13-14, 2024.
    - NW, and NE generators were operated (turned on at about 500PM on Apr 13 and off at about 800PM on Apr 14)
    - 0.85” of precipitation fell during the seeding period at Lytle Creek
    - 10,000’ MSL temperatures -6C good
    - Stability ok,
    - Winds SW good
    - Cloud bases below 10,000’ MSL at Big Bear
    - Good Case