Assessing the Cloud Seeding Effects from the Santa Barbara County Cloud Seeding Program on the Cuyama Valley

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1 Introduction

In the western US, precipitation from winter storms is critical for many facets of life across the region, including, but not limited to, the economy, ecology and forestry, and water supplies. In addition to ice crystals and snowflakes, the subfreezing portions of winter storm clouds crossing eastern Santa Barbara County frequently have subfreezing liquid water drops (SLW) (Bernstein et. al 2007). These SLW drops will readily freeze onto any surface they come into contact with. Figure 1 shows a huge mountain top rime ice accretion following a Pacific storm. The rime accretion occurred due to the contact and freezing of SLW drops onto equipment. If SLW drops contact ice crystals in clouds then they will freeze on the crystals, causing them to grow large enough to fall out as precipitation. However, the absence of a sufficient number of ice crystals within clouds results in much of the SLW in winter storms remaining within the clouds as small droplets. This results in the moisture crossing the mountains as unrealized precipitation.

Figure 1: Rime ice showing the presence of supercooled liquid water in Pacific storms.

Cloud seeding is a method to add minute ice forming dust particles into SLW clouds. These dust particles interact with the small SLW droplets in the clouds and cause some of them to freeze. The newly formed ice crystals will quickly grow to snowflake sizes utilizing the cloud SLW, and fall to the surface over the cloud seeding target area.

Cloud seeding is typically done from either ground-based generators or flares mounted on aircraft. The generators and flares release minute solid particles of silver iodide dust which quickly enter the clouds and provide ideal surfaces for new ice crystals to form. Once these ice crystals form, they typically grow to precipitation sized particles within 20-30 minutes. The closer the release point of the generators or flares to the seedable clouds, the more likely cloud seeding will be successful. In addition, it’s necessary to locate ground-based generators or fly aircraft tracks about 15 miles upwind from the target area (dependent on what typical storm wind speeds occur). This is optimal to have the seeded precipitation fall within the target area.

Recent well-funded research studies have shown seasonal snowfall/precipitation enhancements of 14% (Manton and Warren, 2011), and recent case studies of storms over Idaho have shown snow water equivalent (SWE) precipitation increases of 0.4mm (0.016”) to 1.3mm (0.05”) per hour across a 930 sq. mile target area, with up to 275 acre-feet of SWE added to the snowpack in 24 minutes (Friedrich et. al 2020).

In this report, a set of 3 research tasks are presented. The first task focused on creating and analyzing multiyear full-winter output from high-resolution numerical weather prediction model output and creating cloud seeding climatologies over the Cuyama Headwaters. In task two the study assesses if the current Santa Barbara Cloud Seeding project is delivering cloud seeding material to the Cuyama target area by collecting precipitation samples from within the target area during seeding operations and analyzing the chemistry of the precipitation. This analysis looked for slightly elevated silver levels, which would confirm whether the generators are well placed and delivering seeding materials to the target area. The final task was to develop a hypothetical cloud seeding program and estimate how much additional precipitation could be added to the Headwaters region.

2 Geography & Santa Barbara Cloud Seeding Project Overview

The headwaters of the Cuyama River reside in eastern Santa Barbara County and northwestern Ventura County, southeast of New Cuyama (Figure 2). The headwaters are part of the southern California Traverse Ranges, with the highest peaks in the Cuyama headwaters area extending to over 8,000’ MSL. The Cuyama River flows generally from east to west through New Cuyama and eventually drains into the Pacific along the west coast of Santa Barbara County.

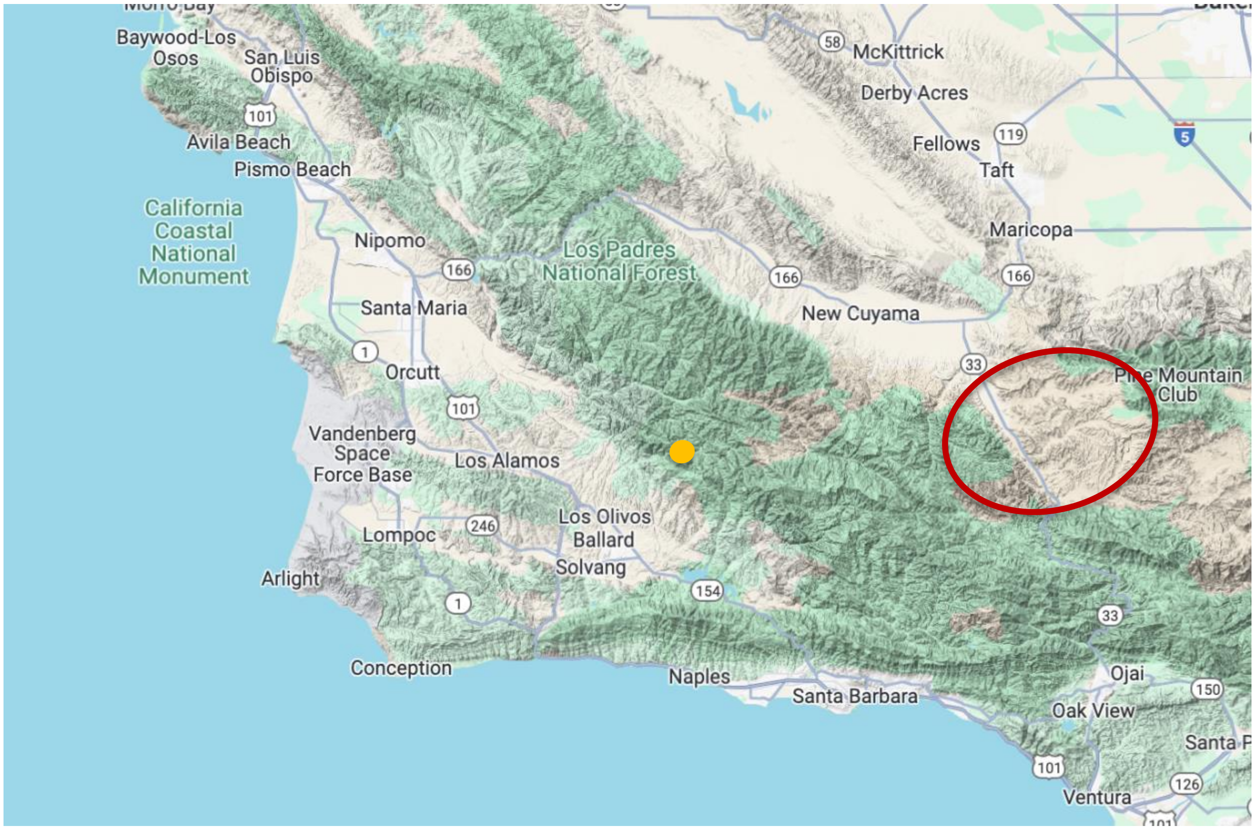

Figure 2: The greater Santa Barbara County terrain map. The red oval shows the location of the Cuyama River Headwaters and the orange dot shows the location of the Figueroa Mountain Rain gauge.

The greater Santa Maria River watershed is shown in Figure 3. The watershed includes the Cuyama River and the Sisquoc River. The existing Santa Barbara Twitchell Reservoir Cloud Seeding project is designed to add water resources to the Twitchell Reservoir. The main rivers and creeks that supply the reservoir include the Cuyama River, Alamo Creek, and the Huasna River.

Figure 3: The Cuyama and Sisquoc River drainages.

The Santa Ynez River watershed in shown in Figure 4. The upper portion of the watershed spans from the eastern edge of Santa Barbara County to Cachuma Lake Reservoir. The water sources feeding Cachuma Lake include the main stem of the Santa Ynez River as well as several creeks that flow south off the higher terrain to the north of the river. These areas make up the Santa Barbara County Santa Ynez (Cachuma) Cloud Seeding project area.

Figure 4: The Santa Ynez River watershed.

The Santa Barbara County Cloud Seeding Program target areas and generator sites are presented in Figure 5. The generator sites are designed to operate under south through westerly wind directions. The Santa Barbara Cloud Seeding Project operates ground-based generators consisting of cloud seeding flares that burn in 4-minute intervals and release short bursts of seeding material. This is in opposition of solution burning ground-based generators, commonly used on other projects, that burn continuously and release seeding material during an entire storm. The project targets the burn of the cloud seeding flares to occur during the short-lived convective bands.

The Twitchell generators are between 100-km (62 miles) and 120-km (75-miles) from the Cuyama headwaters, and the Cachuma generators are between 40-km (25-miles) to 65-km (40-miles) from the Cuyama headwaters. The headwaters of the Cuyama River are not part of the project.

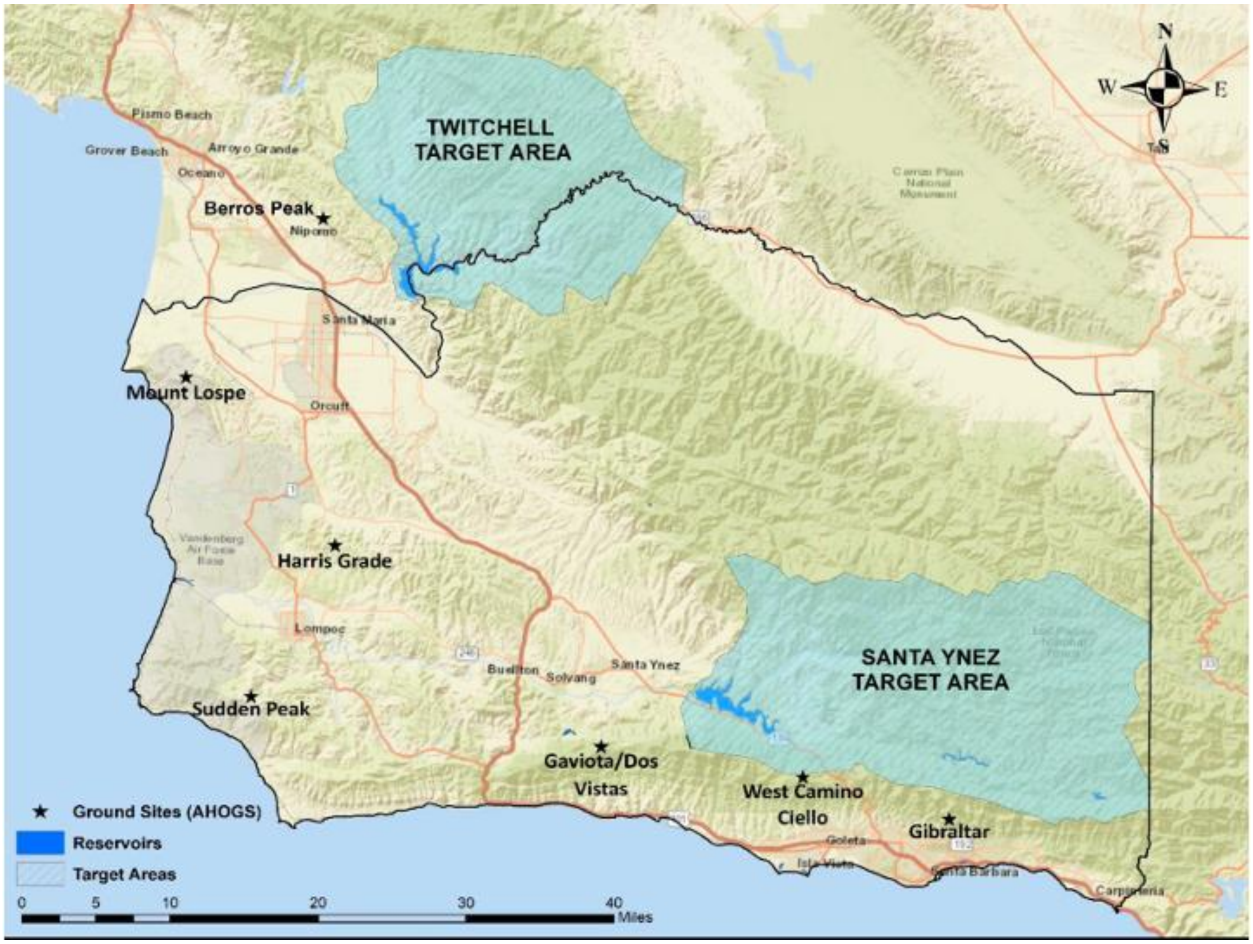

Figure 5: Santa Barbara County Cloud Seeding Project Target Areas (Green Shading) and the 7 Ground Generator Sites (black stars).

3 Analysis

3.1 Task 1: High-Resolution Model Climatology

3.1.1 Task 1 Goals

Understanding the physics of the clouds crossing the Cuyama Headwaters cloud seeding target area is critical for determining the potential for cloud seeding. Clouds must contain SLW at temperatures colder than -5°C to be seedable. Since there are no direct observations of the cloud microstructure (particles within clouds), the main goals for task 1 are to use high resolution numerical weather prediction modeling to identify the time periods, altitudes, winds, and temperatures when cloud seeding conditions are present across the Cuyama Headwaters cloud seeding target area.

3.1.2 Task 1 Methodology

3.1.2.1 Study Time Frame

The study time period consisted of the past 5 years of winter season months (December 1 – March 31) from 1 December 2019 – 31 March 2024. There was a variety of winter seasonal precipitation amounts (as observed at the Figueroa Mountain rain gauge in the mountains of central Santa Barbara County [see Figure 2 for location]). Drought years and very wet years were represented in the study, as well as all three ENSO phases (El Nino, La Nina, and Neutral) (Table 1). In addition, using the past 5 winters for the assessment better represents the current climate regime.

Table 1: Years modeled, precipitation recorded over the Santa Barbara County Mountains at the Figueroa Mountain rain gauge, and the ENSO Phase.

Water Year	Precipitation (Figueroa Mtn)	ENSO Phase
2019-2020	21.57”	Neutral
2020-2021	8.41”	La Nina
2021-2022	13.76”	La Nina
2022-2023	42.94”	La Nina
2023-2024	26.79”	El Nino

3.1.2.2 Numerical Weather Prediction Model Data

Hourly Numerical Weather Prediction (NWP) model data from the analysis runs of the 3-km High Resolution Rapid Refresh (HRRR) model (Dowell et. al., 2022) were used in the climatological analysis. The model uses new observations to initialize the grid each hour. The HRRR includes a state-of-the-art cloud physics scheme with 4 different classifications of cloud particles, including the most advanced depiction of subfreezing cloud liquid water. The cloud scheme also has an advanced (aerosol aware) parameterization as part of its cloud microphysical module and allows convection. Validation of the cloud scheme shows that supercooled liquid water is present in the model at over 75% of the locations where icing (SLW) is reported by aircraft (Thompson et. al, 2017).

A subset of the HRRR grid was identified over the Cuyama Headwaters target area. This three-dimensional high-resolution grid, with 3-km horizontal grid point spacing and 50 vertical levels, formed the basis for the study. Figure 6 shows the horizontal footprint of the target area grid overlaid on a map of the greater Santa Barbara/Ventura County region. The Cuyama Headwaters grid has an 11 x 7 grid footprint. The model fields used in the analysis are listed in Table 2.

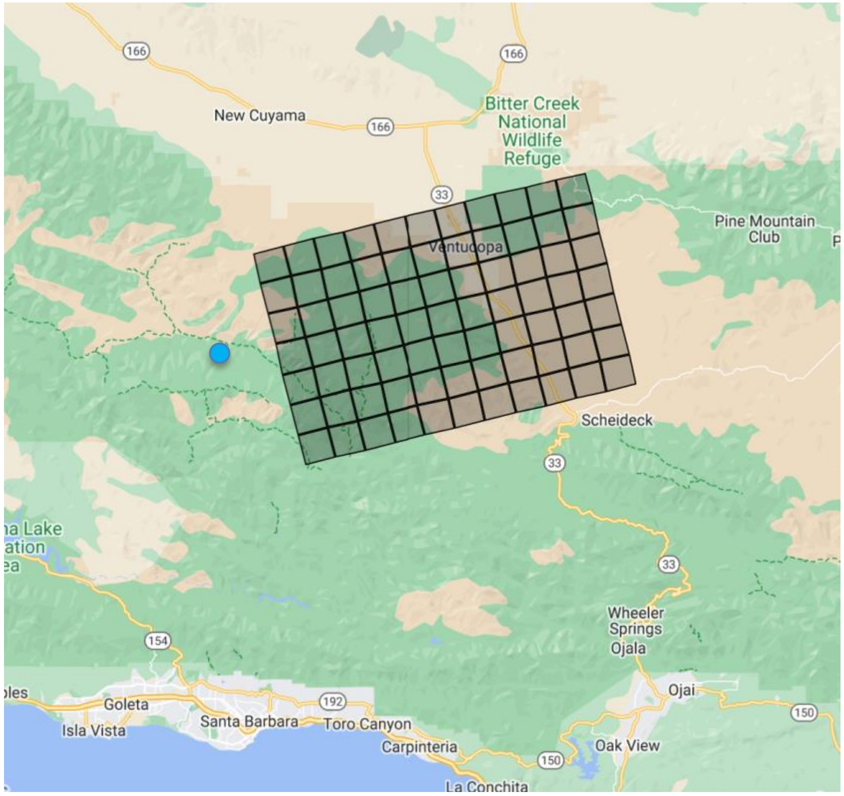

Figure 6: NWP Model Domain for the Cuyama Headwaters Target Area. Blue dot shows the location of the Figueroa Mountain precipitation gauge.

Table 2: Model fields used in the study

GRIB Name	Units
Geopotential Height	Gpm
Cloud Water Mixing Ratio	kg / kg
Temperature	K
U component of wind	m / s
V component of wind	m / s
Pressure	Pa
Specific humidity	kg / kg
Snow Mixing Ratio	kg / kg
Graupel (Snow Pellets)	kg / kg
latitude	Degrees north
longitude	Degrees east

3.1.2.3 Definition of Seedable Conditions

Defining what constitutes favorable seedable conditions for each hourly model update relies on data at each grid cell within the specific target area grid at the appropriate altitudes. Two altitude bands are considered in this study, one relevant for ground-based seeding operations and a second one relevant to aircraft seeding.

The ground-based altitude band looked at all model grid cells between 4,000 and 11,000 feet MSL. This layer is potentially seedable from the ground when the lowest layer of the atmosphere is unstable, allowing uninhibited vertical mixing. The aircraft-based altitude band looked at all model grid cells between 8,000 and 14,000 feet MSL, as these are the altitudes for which an aircraft could seed the area. Next, each grid cell within the target area grid and corresponding altitude band was assessed to determine if the temperature was within the -18^{o}C to -5^{o}C range. The liquid water content of each cell was also assessed. While most studies have used the low threshold of 0.001 g kg^{-1}, essentially looking at whether any liquid water was present at all, this study uses the threshold of 0.135 g kg^{-1} since this is a more realistic minimum amount of cloud water needed to adequately grow precipitation sized snowflakes in the distance between the generators and the target area.

For each hourly model update, a minimum of 5 grid cells within the target area grid, distributed either vertically or horizontally, that satisfied the temperature and cloud water requirements, as outlined above, were needed to signify that seeding conditions were present for that hour. This value was determined by considering grid volume and the growth rate of ice in supercooled liquid water. Figure 7 shows the number of grid cells that satisfy the temperature and liquid water requirements for each model update over the five-year study period for the aircraft-based altitude band over the Cuyama target area. Model hours for which no cells satisfied the conditions, and thus have no seeding potential, are not shown. While requiring at least five grid cells to satisfy the temperature and liquid water requirements to determine seedable conditions does eliminate some seedable hours, as seen in Figure 7, most of the updates show 5-or-more grid cells satisfying the requirements. Note also there is a clear delineation between the number of cases with 4 vs 5 grid cells satisfying the conditions.

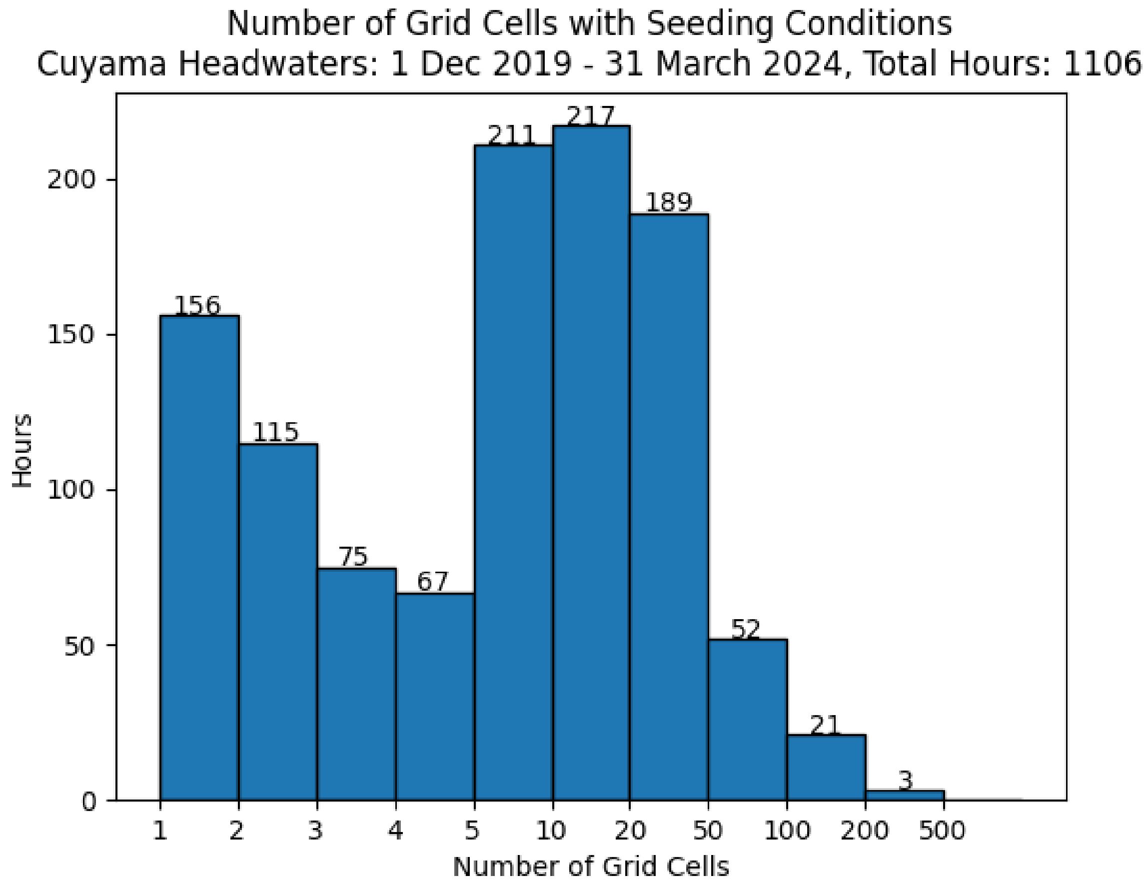

Figure 7: Number of Grid Cells with Seeding Conditions for altitudes relevant to Aircraft-Based Cloud Seeding for the Cuyama target area for WY20-WY24.

The wind speed and temperature during seeding conditions were reviewed as part of the climatology. For ground-based seeding, the median of the wind speed and direction of all the model grid cells closest to 10,000 ft within the target area is reported. For aircraft-based seeding, the median wind speed and direction from 14,000 ft is reported.

Table 3 contains a summary of the definition of seedable conditions for each model update described in this section.

Table 3: Summary of Seedable Conditions Definition

	Ground-based	Aircraft- based
Altitude band:	4,000 – 11,000 ft	8,000 – 14,000 ft
Temperature:	Between -18 and -5 ºC	
Cloud Liquid Water (CWMR)	> 0.135 g kg^{-1}	
Minimum number of Model grid cells satisfying Temperature and CWMR conditions, per hour	5	
Median Altitude of reported Wind Values	10,000 ft	14,000 ft

3.1.3 Climatology Results

3.1.3.1 Cuyama Headwaters Area

3.1.3.1.1 Ground based climatology

The analysis of the hourly ground-based climatology for the Cuyama Headwaters shows that there were 755 hours with seedable conditions across the five-year study period, as shown in Figure 8. As expected, the wettest year, winter 2022-2023 (WY23), had the most seedable hours with 278. Of interest was the driest year, WY21, which had 114 seedable hours, which was similar to the seedable hours present during the wetter year of WY20, and had more seedable hours than the higher precipitation winter of WY22. This suggests that significant cloud seeding opportunities can be present even during very dry years.

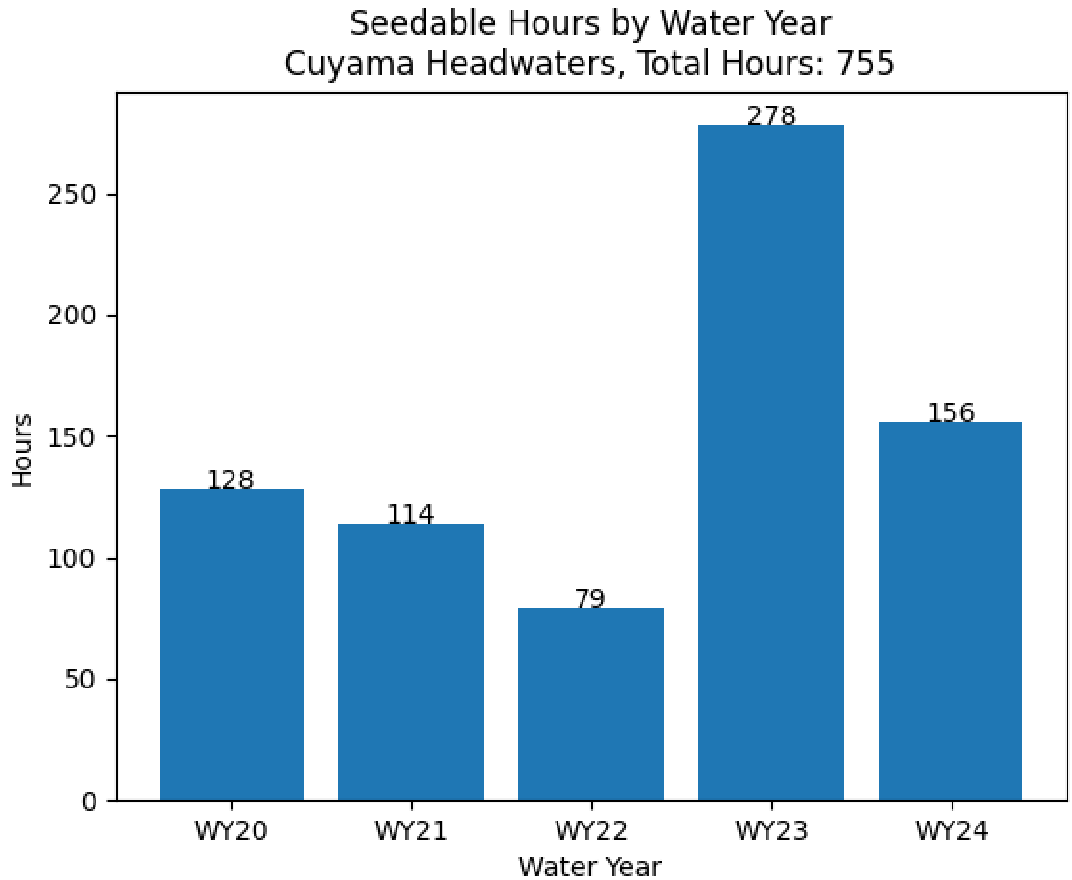

Figure 8: Seedable Hours by Water Year for ground-based seeding over the 5-year Study Period WY20-WY24 for the Cuyama Area.

Next, the duration of the cloud seeding periods were determined. Figure 9 shows the duration of periods with consecutive hours with cloud seeding conditions, denoted as an event. The majority of events are short and fleeting, with 72% of the 259 events shorter than 3 hours, and nearly all of them shorter than 12 hours. However, the events lasting less than 3 hours only make up 27% (206 of 755) of the total seedable hours for the Cuyama Headwaters region. Due to the fleeting amounts of liquid water in the short duration seeding periods and the limited time to create and grow newly formed ice crystals to precipitation sized snowflakes, only events 3 hours long or greater were considered seedable for operational cloud seeding purposes for this study. The operational seedable hours by water year using the 3-or-more hour threshold is shown in Figure 10 and shows a total of 549 hours over the 5-year study period.

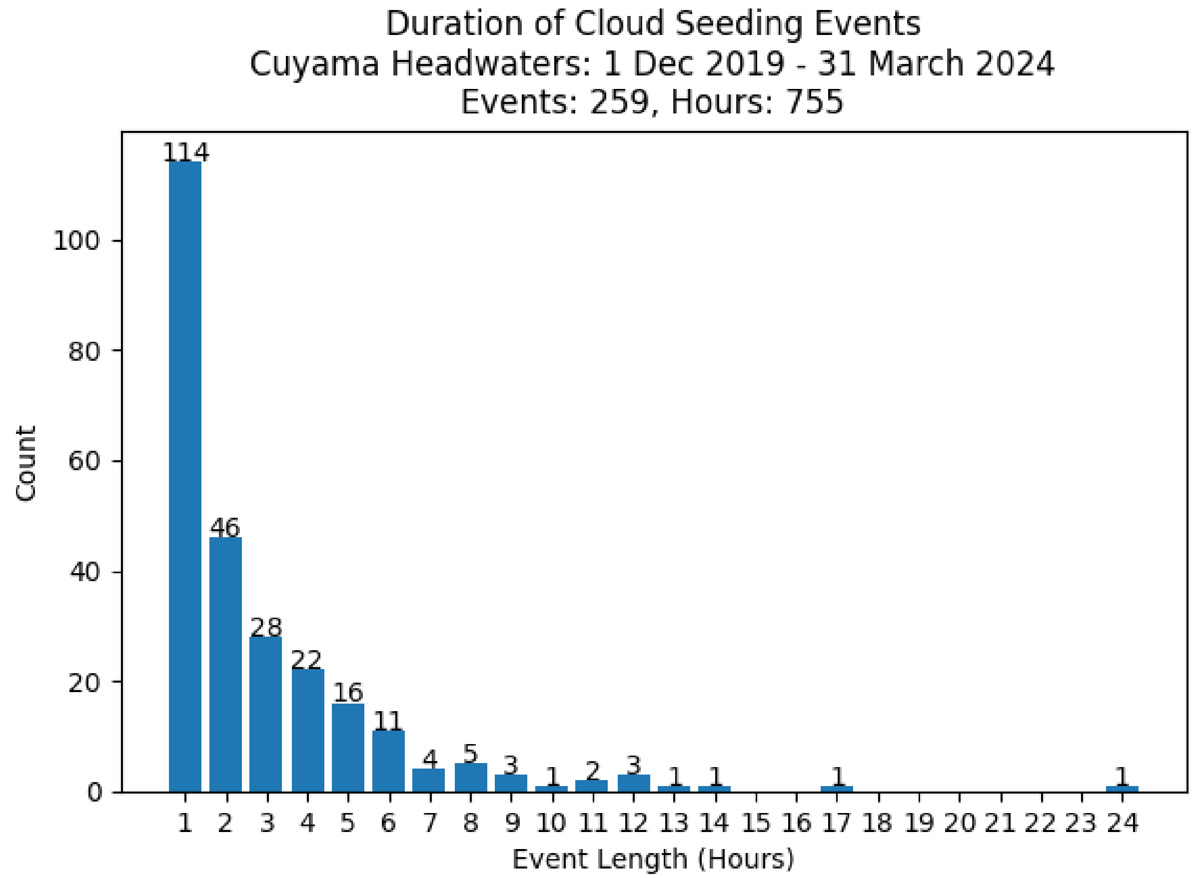

Figure 9: Duration of Cloud Seeding Events for ground-based seeding over the 5-year Study Period WY20-WY24 for the Cuyama Target Area.

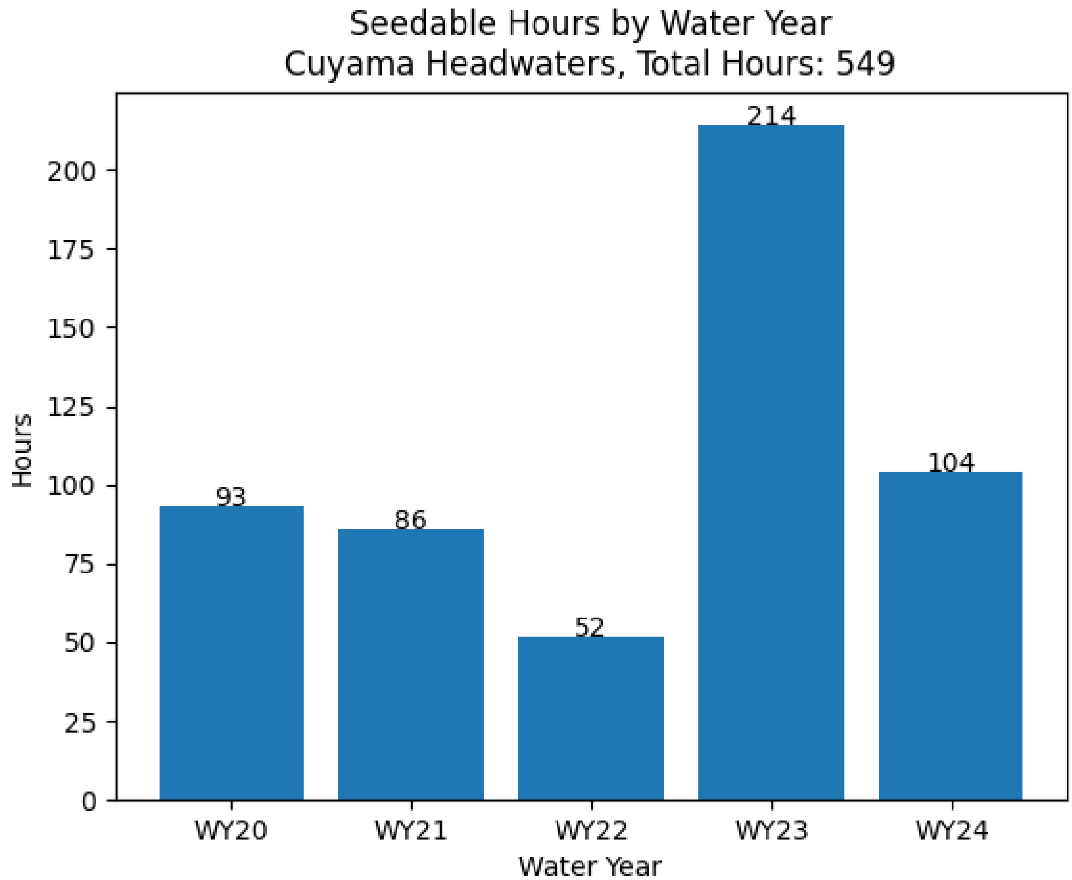

Figure 10: Seedable Hours by Water Year for ground-based seeding over the 5-year Study Period WY20-WY24 for the Cuyama Area for Events lasting at least 3 consecutive hours.

Figure 11 shows the filtered seedable hours by month for the 5-year study period. The most seedable hours for the 5-year study period occur in the month of March, with 242 hours, which is about double the number of hours when compared to the largest number of seedable hours from the other months. This was due to the fact that the coldest storms of the season typically arrive in March. The coldest storms have a lower height of the seedable portions of the clouds which increases the chances for successful vertical mixing from ground-based seeding.

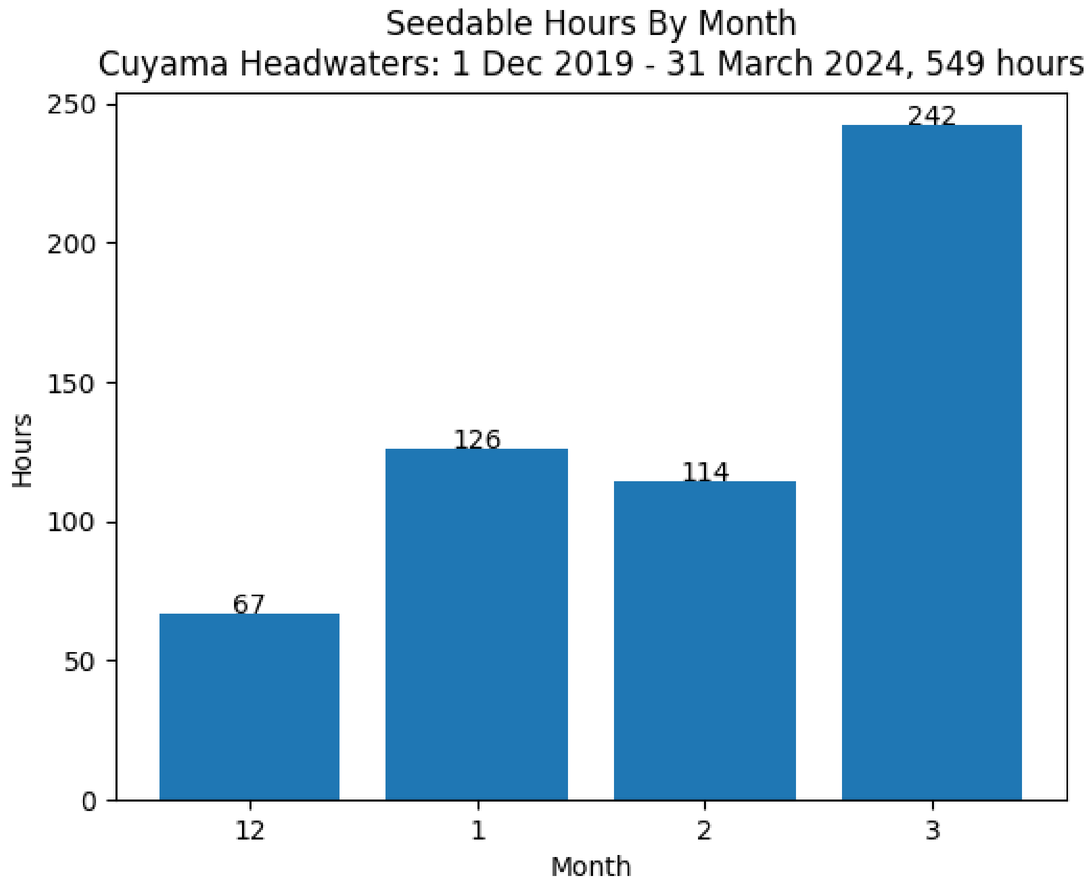

Figure 11: Seedable Hours by Month for ground-based seeding over the 5-year Study Period WY20-WY24 for the Cuyama Target Area for events lasting at least 3 consecutive hours.

The most common seeding level winds (10,000 ft MSL) during ground-based seeding conditions were from the southwest through west (Figure 12). During most California winter storms (mid latitude cyclones) these wind directions are associated with the approach and passage of the cold fronts. The wind directions are also clearly shown to be on-shore, bringing moisture off the Pacific. The wind speeds associated with seeding periods were relatively strong, typically greater than 30MPH.

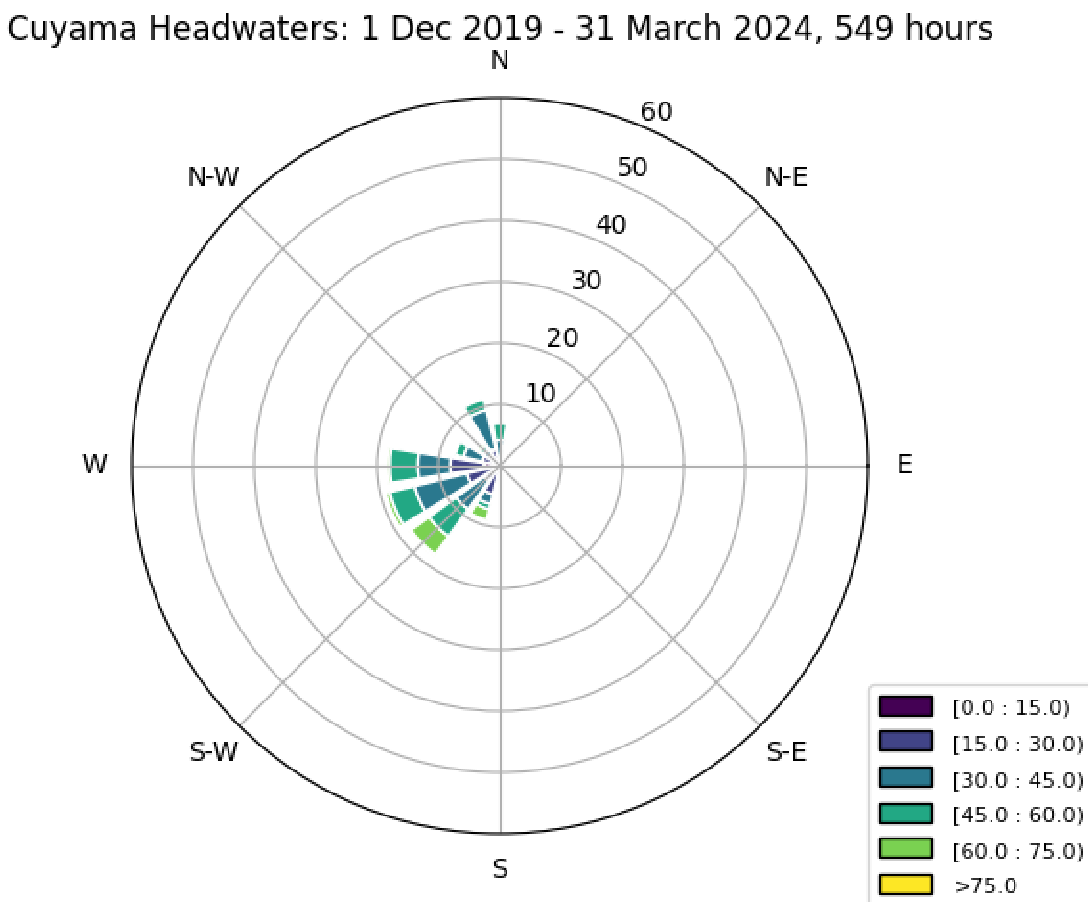

Figure 12: Wind Rose showing the 10,000 ft Wind Speed (MPH) and Direction when Seedable Conditions are Present for ground-based seeding over the 5-year Study Period WY20-WY24 for the Cuyama Target Area for Events lasting at least 3 consecutive hours.

3.1.3.1.2 Aircraft based climatology

The results of the hourly aircraft-based climatology for the Cuyama Headwaters Project show that there were 6*93* hours with seedable conditions across the five-year study period (Figure 13). This is 63 less hours than was identified for the ground-based seeding. Similar to the ground-based climatology, the wettest year winter 2022-2023 (WY23) had the most seedable hours with 232. Unlike the ground-based results, the frequency of seedable hours was more closely tied to the yearly precipitation.

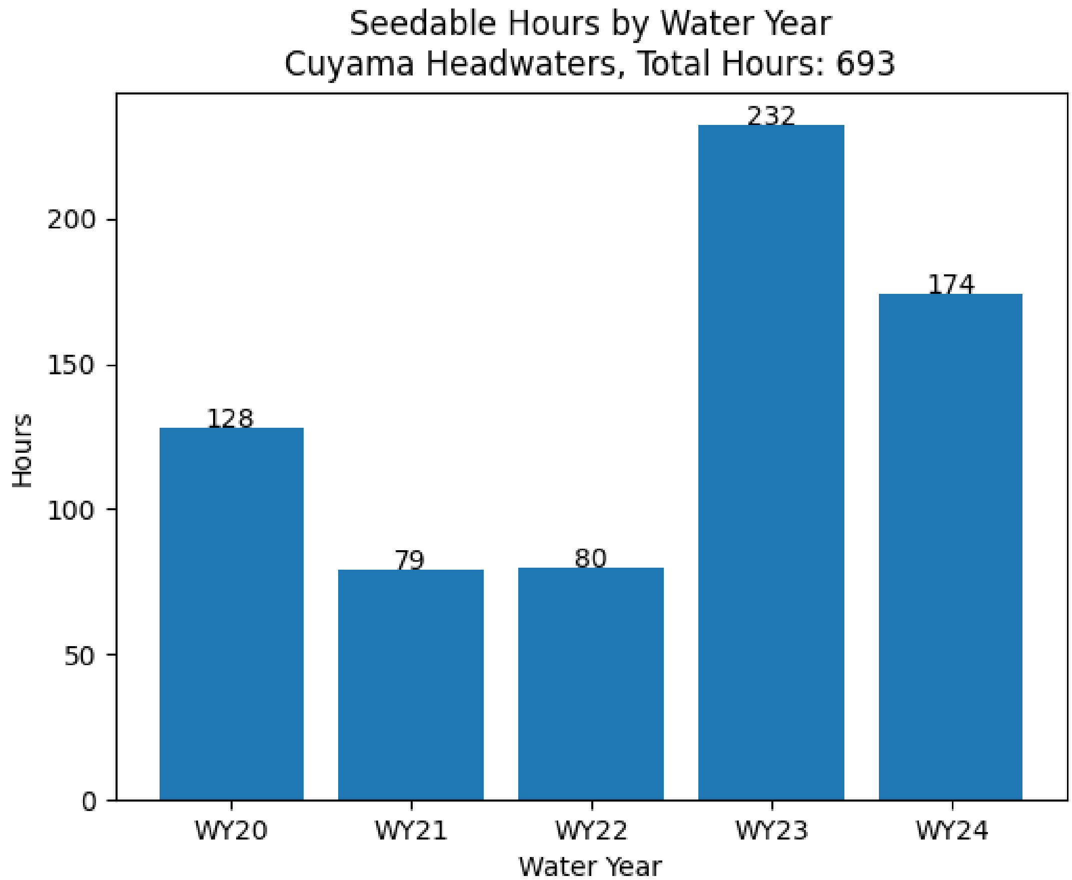

Figure 13: Seedable Hours by Water year for aircraft-based seeding over the 5-year Study Period WY20-WY24 for the Cuyama Headwaters Area.

Next the duration of events, or periods with consecutive hours exhibiting cloud seeding conditions, for Cuyama Headwaters aircraft-based seeding were determined (Figure 14). As with the ground-based seeding, the majority of aircraft seeding events are short and fleeting, with 68% of the 259 events shorter than 3-hours, and nearly all of them shorter than 12-hours. However, the events less than 3 hours only make up about a third (229 of 652 or 35%) of the total seedable hours for the region. Similar to ground-based seeding, due to the fleeting amounts of liquid water in the short duration seeding periods and the limited time to create and grow newly formed ice crystals to precipitation sized snowflakes, only events 3 hour long or greater were considered seedable for operational cloud seeding purposes for this study. The filtered aircraft seedable hours using the 3-or-more hour threshold is shown in Figure 15. A total of 429 hours of aircraft seeding, within 3-or-more consecutive hour storm periods, were identified.

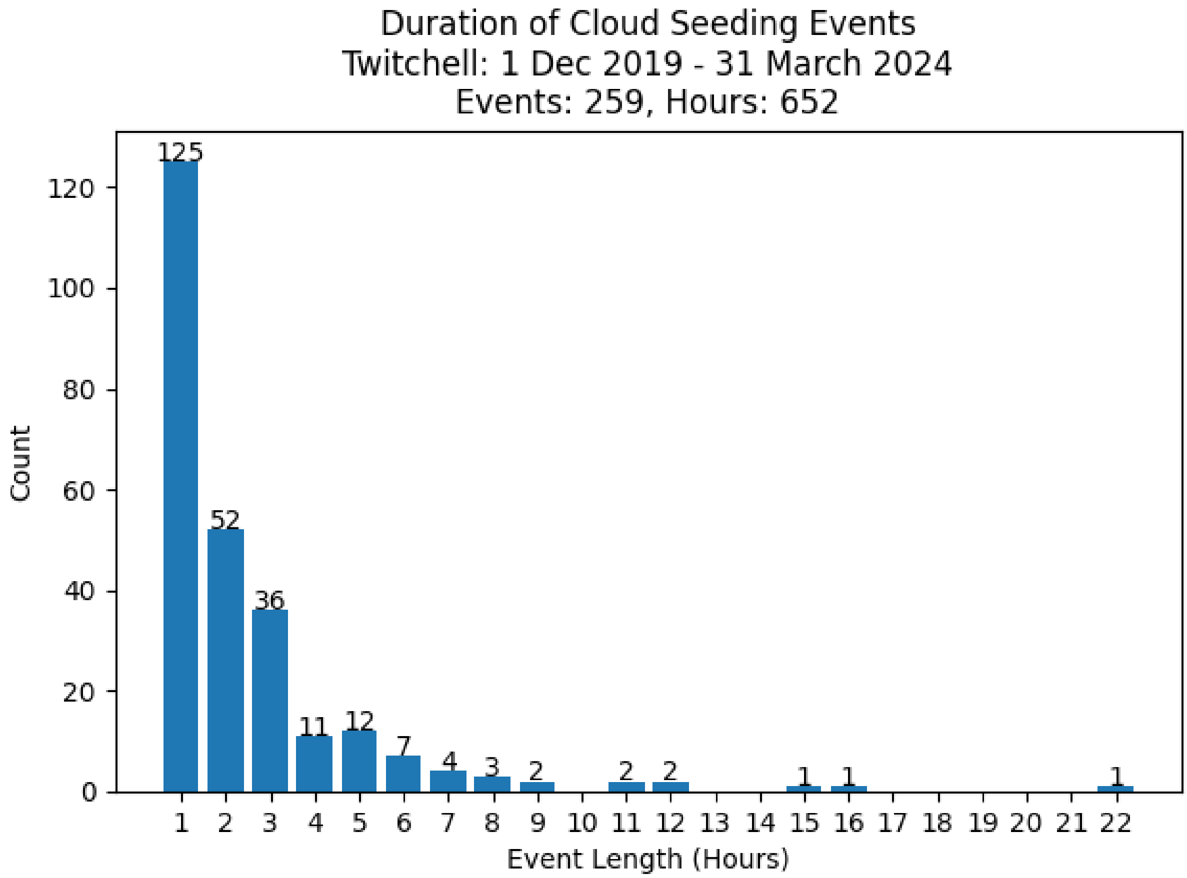

Figure 14: Duration of Cloud Seeding Events for aircraft-based seeding over the 5-year Study Period WY20-WY24 for the Cuyama Target Area.

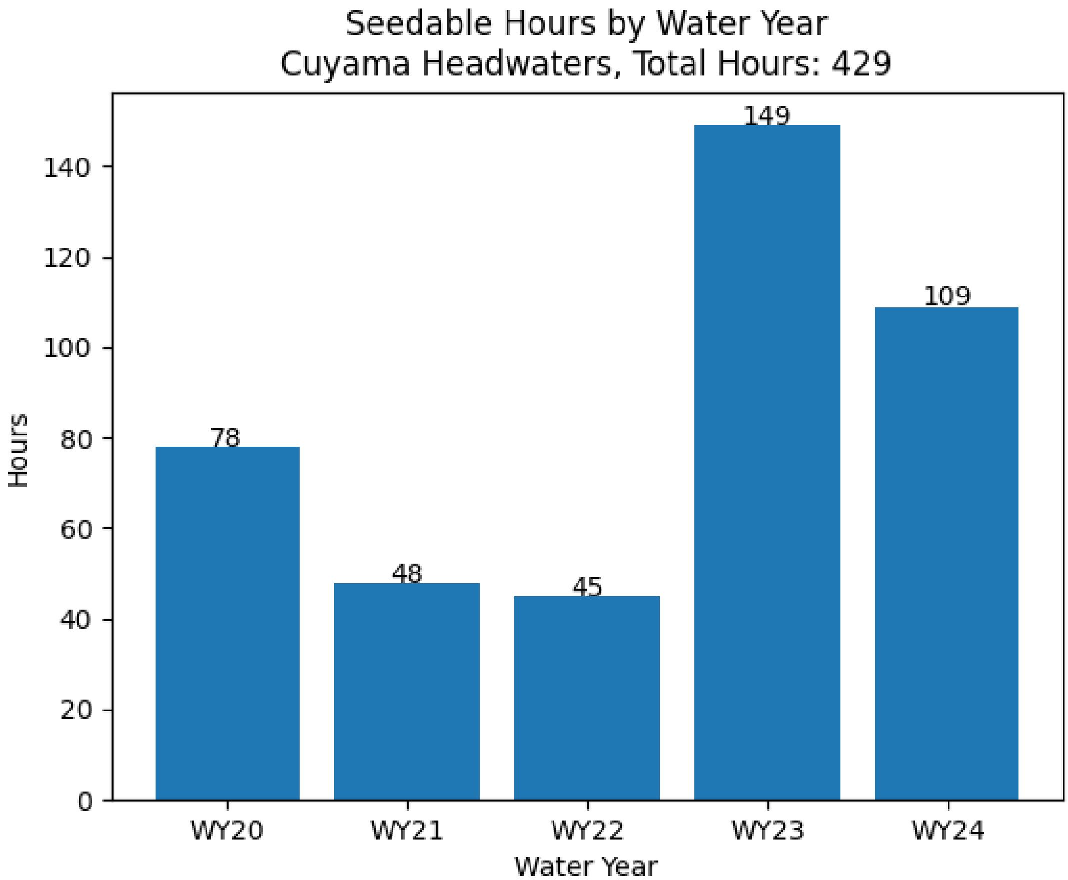

Figure 15: Seedable Hours by Water year for aircraft-based seeding over the 5-year Study Period WY20-WY24 for the Cuyama Target Area for events lasting at least 3 consecutive hours.

Figure 16 shows the filtered seedable hours by month for the 5-year study period. March had the most opportunities for cloud seeding with 167 hours (Figure 16). Unlike the ground-based results where the hours in March were about double that of the other months, significantly more opportunities relative to March were found in December and January, which had 77 and 94 hours, respectively. This is due to the fact that storm temperatures are nearly always cold enough for aircraft seeding at 14,000' MSL.

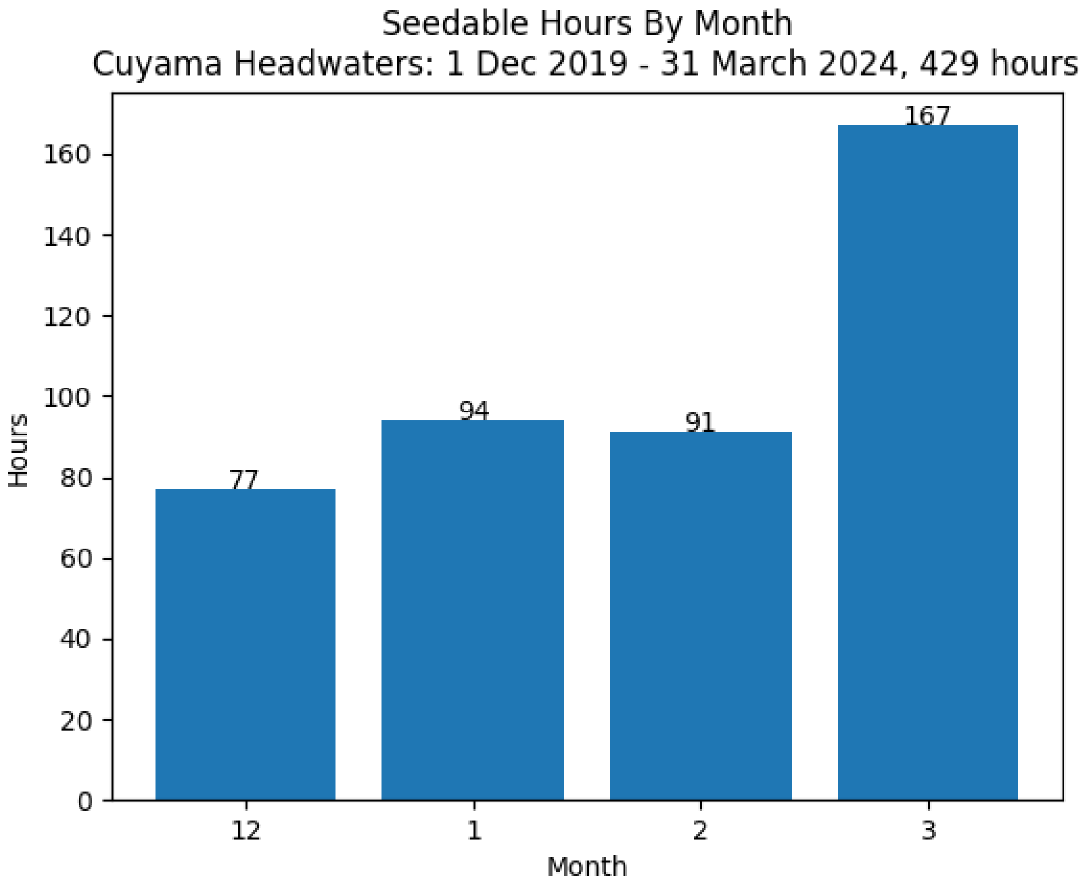

Figure 16: Seedable Hours by Month for aircraft-based seeding over the 5-year Study Period WY20-WY24 for the Cuyama Target Area for events lasting at least 3 consecutive hours.

The most common seeding level winds (14,000' MSL) during the Cuyama aircraft-based seeding conditions were from the southwest through west-southwest (Figure 17), similar to the ground-based results. During most California winter storms (mid latitude cyclones) these wind directions are associated with the approach and passage of the cold fronts. The winds directions are also clearly shown to be on-shore, bringing moisture off the Pacific. The wind speeds associated with the aircraft seeding periods were stronger than seen for the ground-based results, typically greater than 45 MPH, with some median speed values larger than 75 MPH.

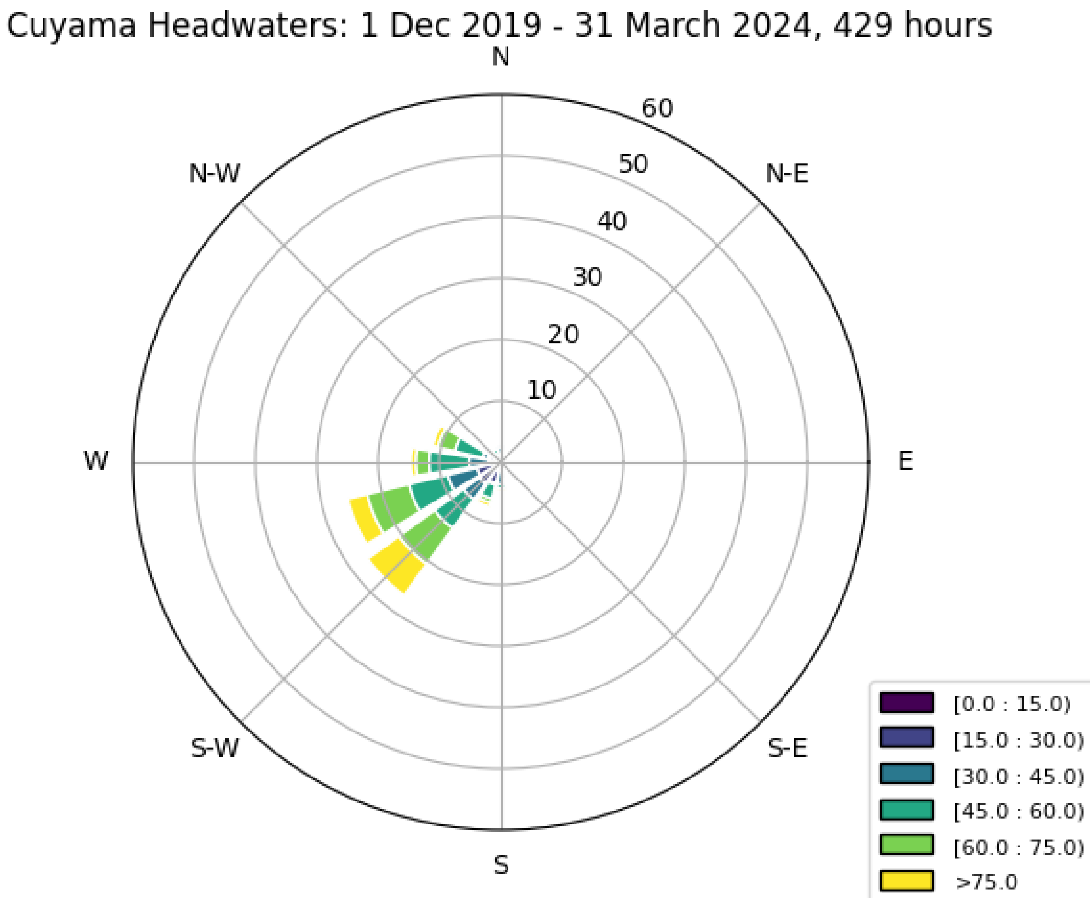

Figure 17: Wind rose showing the 14,000 ft wind speed and direction when seedable conditions are present for aircraft seeding over the 5-year Study Period WY20-WY24 for the Cuyama Target Area for Events lasting at least 3 consecutive hours.

3.1.4 Climatology Summary

The 5-year climatology using the high-resolution NWP model was completed for both potential ground- and aircraft-based cloud seeding over the Cuyama Headwaters. The results showed that cloud seeding opportunities were present during both dry and wet years. All of the periods that were considered seedable from the ground required 3-or-more consecutive hours of seeding conditions. Using the 3-or-more consecutive hours to define seeding activities allows sufficient time for ground-based generators to be started and aircraft to be deployed and conduct seeding.

The climatology results show there were a significant number of seeding opportunities over the Cuyama target area for both aircraft (429-hours) and ground (549-hours). These opportunities are likely due to the moist onshore flow associated with winter storms having increased orographic lift over the higher terrain of the northeastern side of Santa Barbara County and the northwestern side of Ventura County. March had the most opportunities, due to storm frequency and colder temperatures. The aircraft seeding opportunities were somewhat more evenly spread across the winter.

Based on the wind direction analysis, generators and aircraft track should be located to the west-southwest of the project area. Winds speeds suggest that the ground-based equipment would be sited about 15 miles away from the target area, and the variable distance aircraft fracks would range from 20 to 30 miles west or southwest of the target area.

3.2 Task 2: Targeting Assessment Using Snow Chemistry

3.2.1 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^{o}C and the newly formed seeded snow is deposited in the target area. Successful targeting can be potentially proven 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 fresh snow/precipitation compared to about 4 parts per trillion (ppt) in unseeded. With the project location so close to the Coast, storm winds are typically onshore. Since very limited crustal silver is found over oceans, we expect very low values of silver in observed unseeded precipitation. This means that a lower positive threshold of 3-4 ppt may show successful targeting. For this study, 4 parts per trillion (ppt) was used as the threshold to delineate between seeded and unseeded precipitation.

It should be noted that in soil samples in the western US silver is found in the 10s to 100s of parts per billion to parts per millions, depending of the geography and geologic history of the area. This is 100,000 times more than the quantities of silver typically found in fresh seeded precipitation.

DRI personnel collected precipitation samples during one winter storm event. The collections were done in the Cuyama Headwaters and several locations across the active Santa Barbara Twitchell target area cloud seeding program. Unfortunately, the Santa Ynez-Cachuma project was suspended for the winter 2023-2024 winter and no active seeding was conducted during the collection period. Figure 18 shows the collection locations on a topographic map of the Twitchell and Cuyama Headwaters target area.

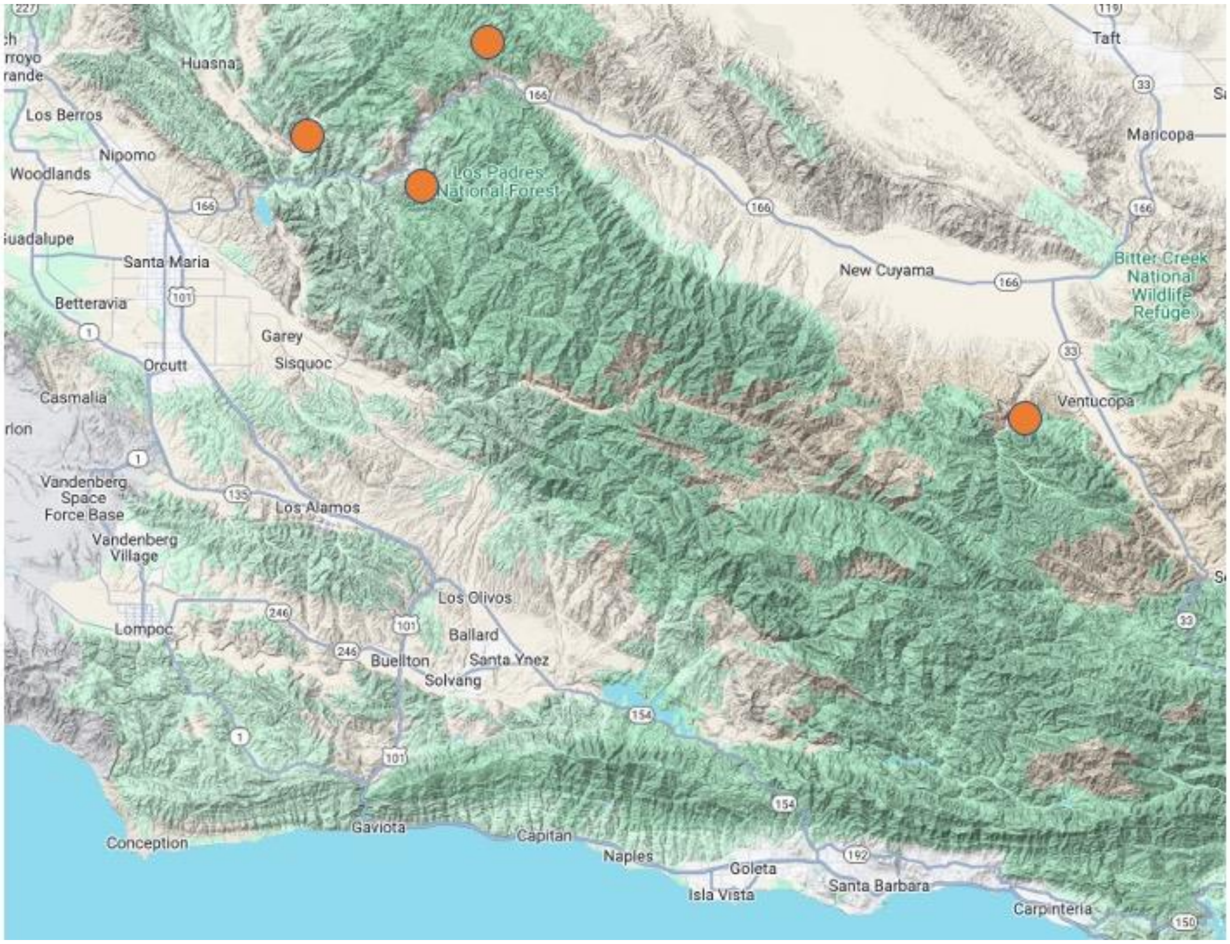

Figure 18: Topographic map of Greater Cuyama River area. Orange dots show the precipitation collection locations for the February 1, 2024 seeded storm. The Alamo Creek site is on the west side of the image. The Willow Springs site is on a ridge to the southeast of Alamo, the Cable Corral site in to the northeast. The Cuyama Headwaters site was in the Santa Barbara Canyon on east side of image.

Figure 19 shows the general precipitation sampling process (shown for snow in the figure). Prior to the storms, precipitation collection tubes with sterile bags were deployed to catch falling rain. After the storm events, the collection tubes and bags with the fresh samples were collected and quickly frozen with dry ice to minimize the samples moving around within the sterile bags. Next the samples were transported frozen to DRI. 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, 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.

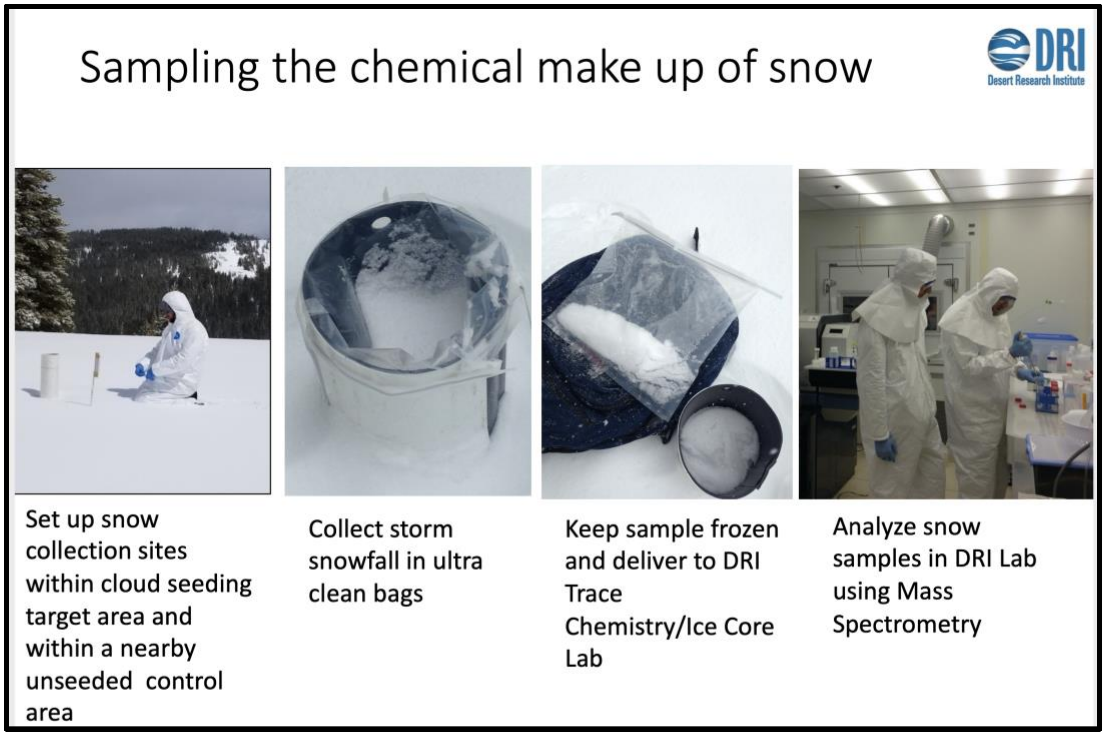

Figure 19: DRI snow chemistry collection and analysis methods

3.2.2 Snow Chemistry Collection Case Analysis

On Jan 31, 2024, a trough and associated cold front were approaching the central California Coast. Four collection tubes were set up in the morning and early afternoon of January 31, 2024 at Santa Barbara Canyon, Alamo, Willow Springs, and Cable Corral, ahead of the arrival of the clouds and precipitation associated with the weather system (see Figure 18 for locations). The storm moved into the area during the evening of January 31 and the early morning of February 1, 2024. Figure 20 shows the 10,000’ MSL (700mb) upper air weather map valid at 1100 UTC. Moisture associated with a cold front is seen moving across the area under southwesterly winds. Seeding was conducted during evening of Jan 31, 2024 - Feb 1, 2024 between 1237AM and 0151AM PST, and another 4-minute flare was burned at 0657 AM. The flares were burned at the 3 generator sites along the western Santa Barbara Coast (Lopse, Harris, Berros [see Figure 5 for locations]).

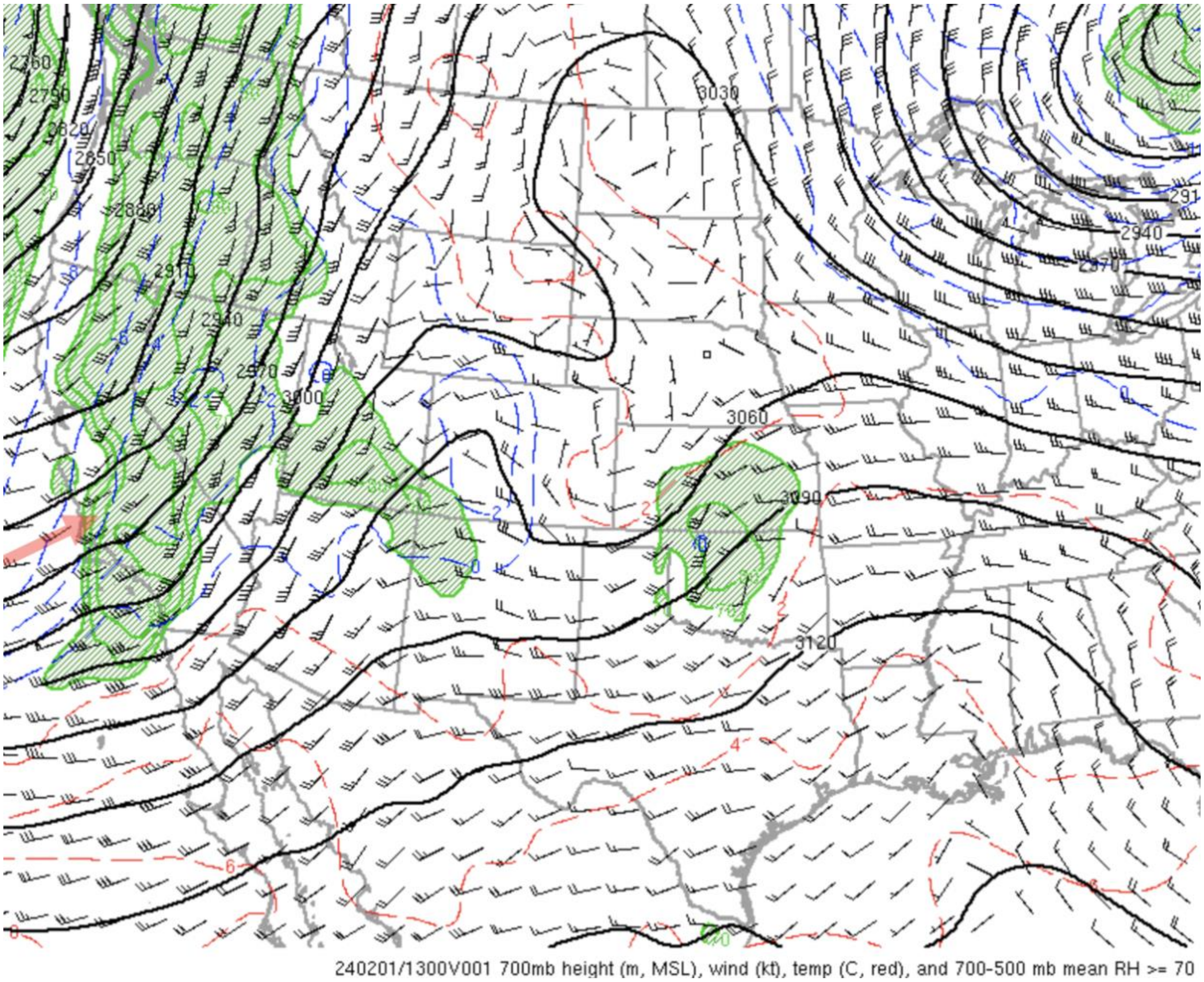

Figure 20: Case 1: February 1, 2024 at 1100 UTC (3AM PST) 10,000' MSL (700mb) upper air weather map. Moisture (green shading) associated with a cold front (blue dashed lines) is seen moving across the area under southwesterly winds

3.2.3 Collection Results

Precipitation samples were obtained from the four collection locations on the early afternoon of February 1, 2024. The weather maps showed the wind directions and associated seeding plumes from the cloud seeding generators would have moved into the active Twitchell target area, and potentially into the distant Cuyama Headwaters area during the storm. Table 4 gives the values of silver found in the precipitation collection samples for the January 31, 2024 – February 1, 2024 storm for each collection location. The samples show slightly elevated silver concentrations at all three collection locations in the Twitchell target area, but nothing (< 1ppt) in the Santa Barbara Canyon sample. It is worth noting that the Santa Barbara County Twitchell Project sample values were much lower than is typically found in other projects, being between 3.7 to 7.1 ppt, but very low amounts of silver are typically released during flare-based seeding operations, so these results may show that seeding material was captured in the precipitation samples. The results suggest that the Twitchell Project was not seeding the Cuyama Headwaters region during this storm.

Table 4: Amount of Silver Measured from Precipitation Collection Samples.

	Collection Location			
Storm Date	**Santa Barbara Canyon**	**Alamo**	**Willow Springs**	**Cable Corral**
Jan 30 – Feb 1, 2024	< 1 ppt	7.1 ppt	6.6 ppt	3.7 ppt

3.2.4 Snow Chemistry Discussion

While only one sample was collected from one storm for the Cuyama target area, the results show low values of the seeding materials in the samples from the collection sites within the Twitchell target area and no evidence of a seeding effect in the sample from the Cuyama target area. In terms of temperatures, wind speeds, and directions this storm is fairly representative of many storms crossing the area. The location of the generators being approximately 60 miles away from the Cuyama target area, and wind speeds of 35 MPH covering a 60+ mile distance between the generator release locations, suggests any seeding material will take nearly 2 hours to reach the Cuyama target area. By this time the seeding material would be highly dispersed, and if precipitation was present upwind the seeding material would also be removed. In addition, the short burn times of the ground based-seeding flares (4-minutes) makes it improbable that the current project is having any effect on the Cuyama headwaters, and thus the result of no (< 1ppt) detectible silver in the sample from the target area makes sense. This discussed in more detail in Task 3

3.3 Task 3: Potential Precipitation Increases and Hypothetical Project Design

3.3.1 The current Santa Barbara County project is not seeding Cuyama Headwaters.

The results of the climatology from task 1 showed that when ground seeding conditions are present over the Cuyama Headwaters the winds are typically from the southwest through west with speeds of 30 to 60 MPH (see Figure 12). This suggests that 5 of the 7 generators are upwind of the Cuyama target area during seedable periods of the majority storms. Figure 21 shows the Santa Barbara Cloud Seeding project and generator sites, including the distance from the sites to the Cuyama target area. The 4 sites to the west (Berros Peak, Mount Lopse, Harris Grade, and Sudden Peak) are between 57 miles and 68 miles away from the Cuyama Headwaters. This is much too far to successfully seed the potential Cuyama Target area, especially since the generator sites currently use silver iodide flares that only burn for 4 minutes. These distances, coupled with the typical wind speeds between 30 to 60 MPH, means a seeding plume would take between one to two hours to reach the Cuyama area, which isn't realistic due to dispersion of such small seeding plumes. While, generally any seeding effect would occur within about 30 minutes of contact with SLW containing clouds. In addition, wet deposition, which is the removal of atmospheric aerosols that occurs by precipitation capture as rain falls through the atmosphere, would also have removed all of the cloud seeding material well upstream of the Cuyama Target Area. The Gaviota/Dos Vistas generator is southwest of the target area and also within the climatological maximum upstream wind directions. This site, at 47 miles away, is still too far away from the Cuyama headwaters to successfully seed. The two other sites, West Camino Ciello at 34 miles, and Gilbratar at 27 miles, are much closer but still further than the optimal 15 miles away from the Cuyama target area. Those two sites also are to the south-southwest and south of the target area and not in the climatological favored wind directions envelope, and not often operated.

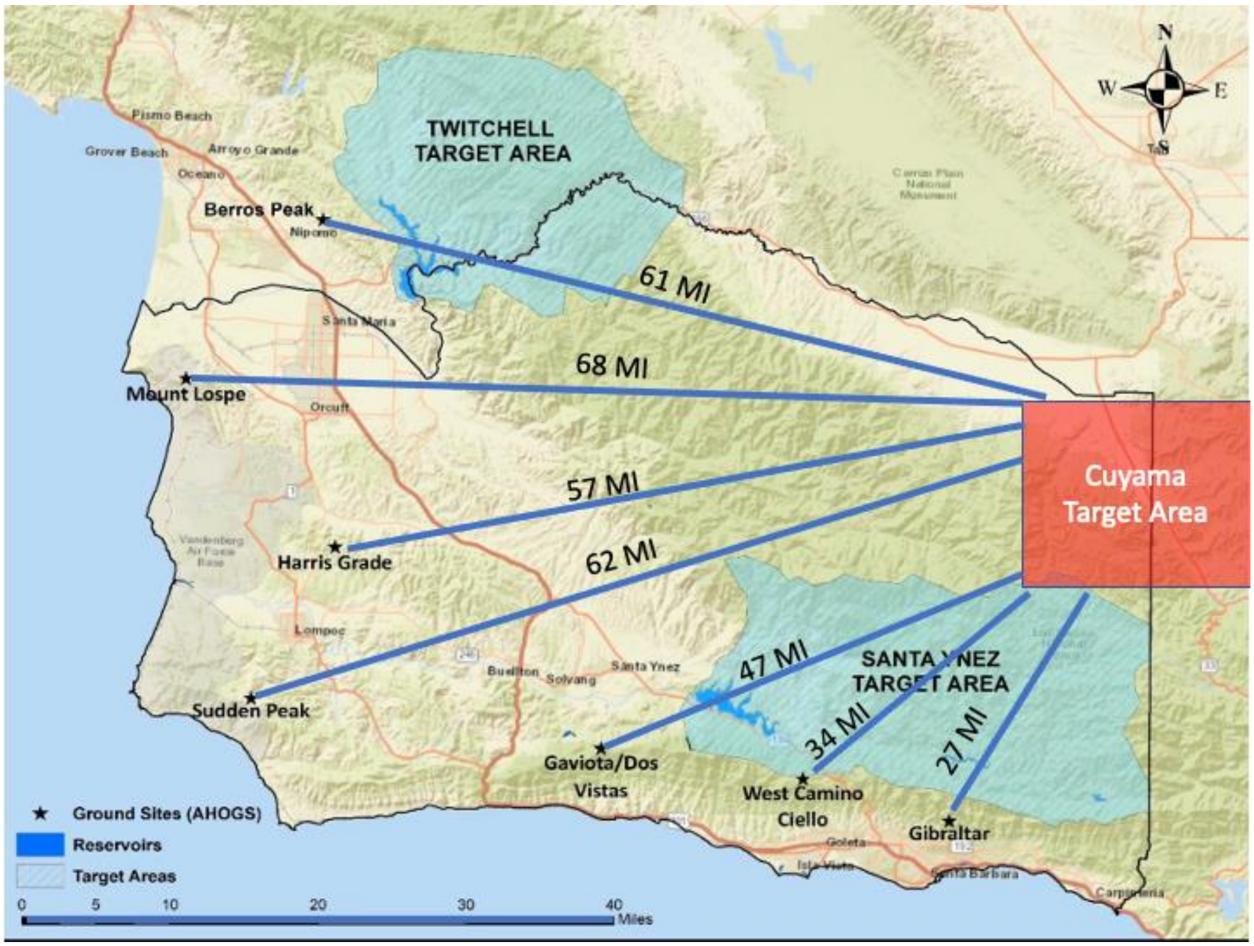

Figure 21: Santa Barbara County Cloud Seeding project areas (green shading), Cuyama Target Area, cloud seeding generators (black stars), Distance each of the generators to the Cuyama target area. generator network

When Twitchell and Santa Ynez (Cachuma) aircraft operations were present the aircraft tracks analyzed would also not have significantly impacted the Cuyama Target area. Similar to the reasons presented about for ground operations, the aircraft tracks were located too far from the Cuyama Headwaters to impact that area.

This analysis along with the snow chemistry shows that the existing Santa Barbara County Cloud Seeding Project is not seeding the Cuyama Headwaters and therefore potential increases from current project do not exist.

3.3.2 Design and results of a potential Cuyama Headwaters cloud seeding project

The results of the analysis from the 5-year climatology study presented in task 1 suggests cloud seeding targeting the Cuyama Headwaters could be done from both the ground or from aircraft.

A ground seeding program would include approximately 4 solution-based generators the continuously produce seeding material, as opposed to the ground-based flare generators. The most ideal locations for these would be on highest terrain available approximately 15-miles to the west and southwest of the target area. A first cut at the placement of 4 ground-based cloud seeding generators are shown in Figure 22.

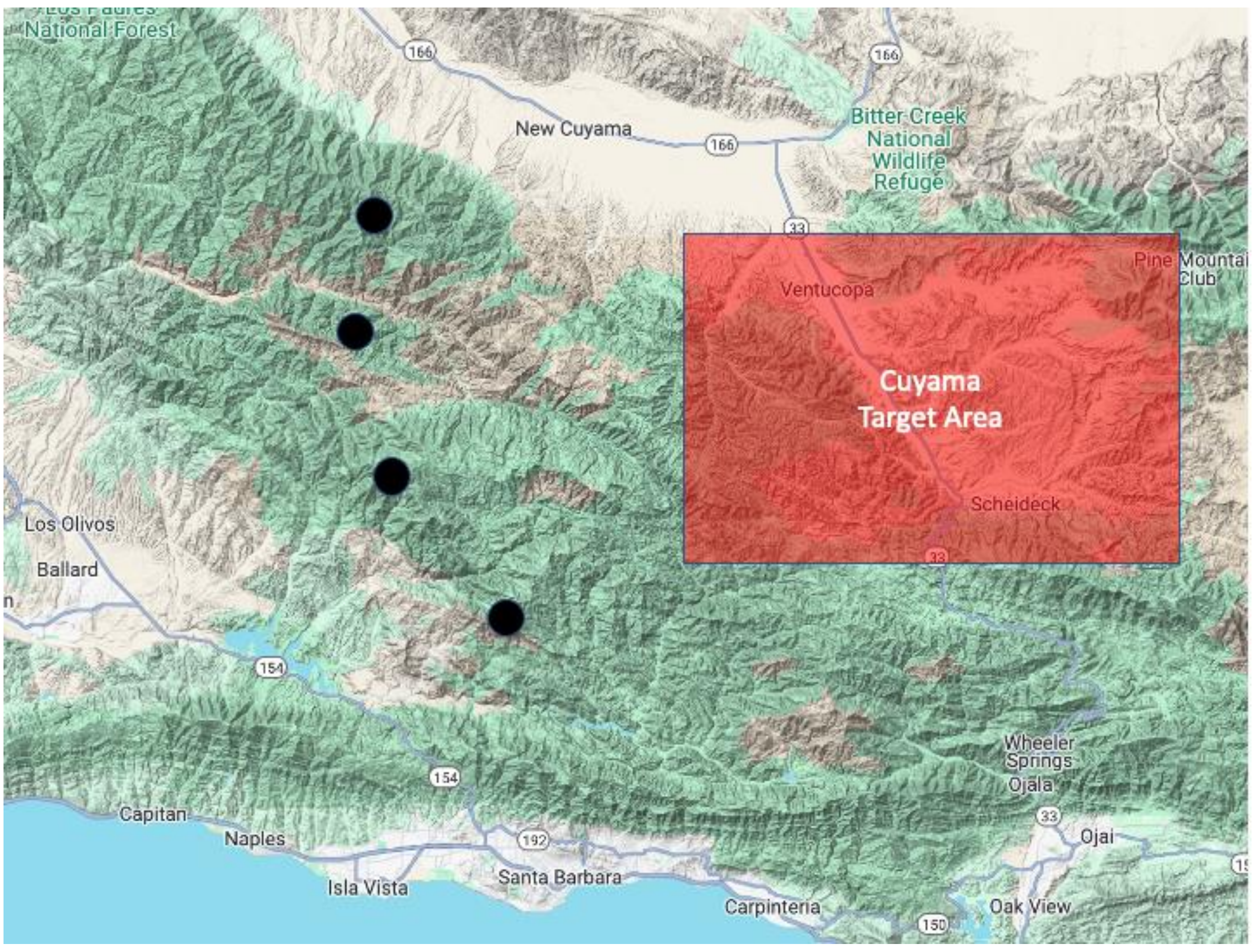

Figure 22. Conceptual model of a ground-based cloud seeding network targeting the Cuyama River Headwaters. Black dots are the cloud seeding generator locations and the red box indicates Cuyama target area.

Ground-based solution generators can produce approximately 20 acre-feet of liquid precipitation per hour, sometime more (Huggins, 2009). If this network was in place during the 5-winters analyzed in section 3.1, and we assume that half of the hours were seeded, then the potential increases in precipitation can be calculated using the below equation, where acre-feet is abbreviated as af. We use 50% due to storm variability, meteorologist forecasting errors, and potential generator mechanical issues.

$$(seeding\ hours) * (4\ generators) * (20\,\frac{af}{hour}) = \text{af of additional water resources}$$

The total acre-feet of additional precipitation for each year are presented in Table 5. The results show that over 2,000 acre-feet of additional precipitation can potentially be produced during the very dry water year 2022 and as much as 8,500 acre-feet could be produced during the wet winter of 2022-2023.

To set up a 4-generator ground program would require a first-year investment in the fabrication of the generators, about $60,000 per generator. Locations for the generators would need to be found and potential land use agreements (typically $500/year) be completed. Since there is already a Santa Barbara County/Cuyama River cloud seeding program, it is currently unclear if a new California Environmental Quality Assessment (CEQA) would be required for this project. Finally, notification in public media would be required to notify the public about the project, and a public meeting in the project area would be required.

Once the project was operational, it would cost approximately $100,000 per year to operate the project. Assuming 5,000 acre-feet could be produced on an average winter the cost-benefit would be $20 per acre-foot of additional precipitation.

Table 5: Potential precipitation increases from a 4-generator network seeding the Cuyama Headwaters.

Water Year	Seeding Hours (hrs)	Number of Generators	Precipitation Increases (acre-feet)
2020	46	4	3,680
2021	43	4	3,440
2022	26	4	2,080
2023	107	4	8,560
2024	52	4	4,160
Total	274	4	21,920

Aircraft seeding can produce up to 200 acre-feet of additional precipitation per hour when cloud seeding conditions are present (Huggins, 2009). Using the flight tracks identified in Figure 23, and assuming that 25% of the defined aircraft seedable hours from sections 3 were flown for each of the 5 water years, then the potential increases in precipitation can be calculated using the below equation, where acre-feet is abbreviated as af. We use and estimate of 25% due to aircraft operational restrictions, pilot rest time, and refueling time.

$$(seeding\ flight\ hours) * \left(200\,\frac{af}{hour}\right) = af\ of\ additional\ water\ resources$$

The results for a hypothetical aircraft program are shown in Table 6. The results show that 2,200 acre-feet of additional precipitation could be produced during the dry water year 2022 and as much as 7,600 acre-feet of additional precipitation could be produced during the wet water year 2023.

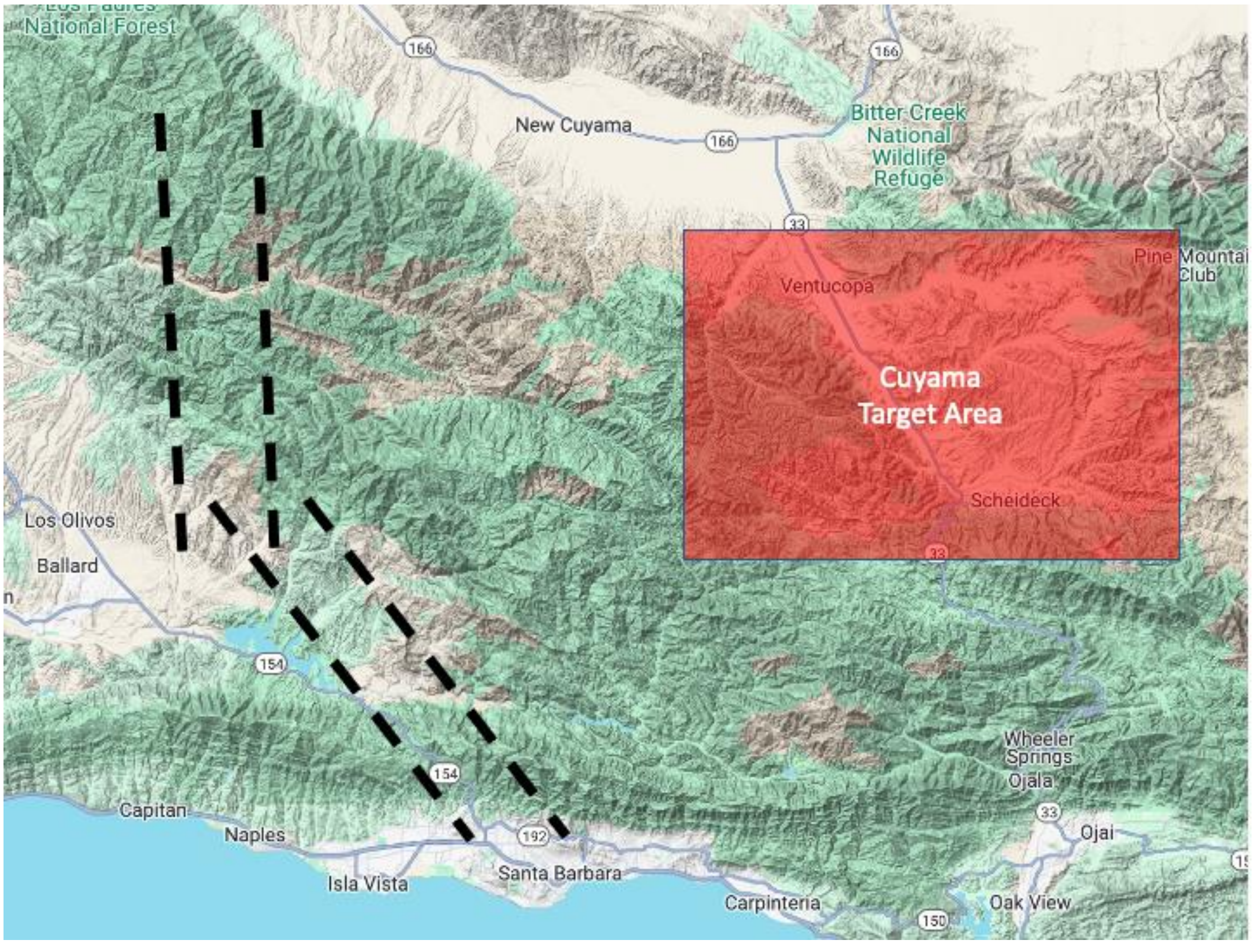

Figure 23: Conceptual model of an aircraft-based cloud seeding network targeting the Cuyama River Headwaters. The dashed lines indicate the potential aircraft seeding flight tracks and the red box indicates the Cuyama Target area.

Table 6: Potential precipitation increases from an aircraft seeding program targeting the Cuyama Headwaters.

Water Year	Flight seeding hours (hours)	Precipitation Increases (acre-feet)
2020	20	4,000
2021	12	2,400
2022	11	2,200
2023	38	7,600
2024	28	5,600
Total	109	21,800

To set up an aircraft program may require an environmental assessment to be completed. Since there is already a Santa Barbara County cloud seeding program, it is currently unclear if a new California Environmental Quality Assessment (CEQA) would be required for this project. Notification in public media would be required to notify the public about the project, and a public meeting in the project area would be required.

Once the project was operational, it would cost approximately $200,000 per year to conduct 20-hours of aircraft seeding. The aircraft seeding results would produce between 200 – 500 acre-feet per hour, with as much 10,000 acre-feet possible. The cost-benefit for this best-case scenario would be $20 per-acre foot.

4 Summary Of Findings

This study assessed if the storms crossing the headwaters region of the Cuyama River had cloud seeding conditions, and if the existing Santa Barbara County cloud seeding program was currently seeding the Cuyama Headwater area.

The results of the study showed that the headwaters region of the Cuyama River are indeed seedable from both the ground and from the air during both dry and wet years. The month of March had by far the highest number of seedable events. The existing Santa Barbara County cloud seeding program is most likely not having an impact in this area, due to the long distances between the cloud seeding equipment and the Cuyama Headwaters. No cloud seeding signature was found from the precipitation chemistry collection effort.

A hypothetical cloud seeding program was designed and the results showed the potential for at least 2,000 acre-feet of additional precipitation could have been produced on the driest year of the study and over 8,000 acre-feet could have been produced on the wet years.

5 Recommendations

1) Contact Santa Barbara County and see if the Twitchell Program would benefit by seeding the Cuyama Headwaters.

2) Increase precipitation gauge numbers in the target area.
3) Set up a single ground-based solution-burning generator or aircraft project and operate a 2-year pilot program to determine the success of a seeding program.
4) Do several additional rounds of precipitation, soil, and stream chemistry over the area to establish base-line values. Then do extensive precipitation chemistry analysis during the pilot program.

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