Feasibility/Design Study for a Winter Cloud Seeding Program in the San Antonio and Nacimiento Drainages, California

Prepared for

Monterey County Water Resources Agency

by

Don A. Griffith, CCM
Stephanie D. Beall
Todd R. Flanagan
David P. Yorty

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Report No. WM 17-3
Project No. 16-379

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1.0 INTRODUCTION

The Monterey County Water Resources Agency (MCWRA) contacted North American Weather Consultants (NAWC) on August 25, 2016 about the possibility of NAWC performing a feasibility/design study for the Nacimiento Reservoir and San Antonio Reservoir drainages (NRSAR) located in northern San Luis Obispo County and southern Monterey County; respectively. NAWC submitted a proposal to perform such work. A contract was then approved to perform this work on November 14, 2016. The stated goal of this program would be to augment the natural precipitation that occurs in the target area to provide additional inflow into these two reservoirs. Figure 1.1 provides the location of the proposed target areas. This work was to be completed in conjunction to a similar study that NAWC conducted for the San Luis Obispo County Flood Control and Water Conservation District (District). NAWC performed the feasibility/design study for the Lopez Lake and Salinas Reservoir drainages located in southern San Luis Obispo County (Griffith, et al, 2017).

NAWC was contracted to perform the following tasks for MCWRA:

- Task I – Provide a Brief Description of Cloud Seeding Theory
- Task II – Review and Summary of Relevant Prior Studies and Research
- Task III – Review and Analysis of the Climatology of the Target Area
- Task IV – Development of a Program Design
- Task V – Develop Estimates of Seasonal Increases in Precipitation and Stream Flow
- Task VI – Development of Benefit and Cost Estimates
- Task VII – Final Report Preparation

The following sections of this report summarize the work performed in completing the first six tasks.

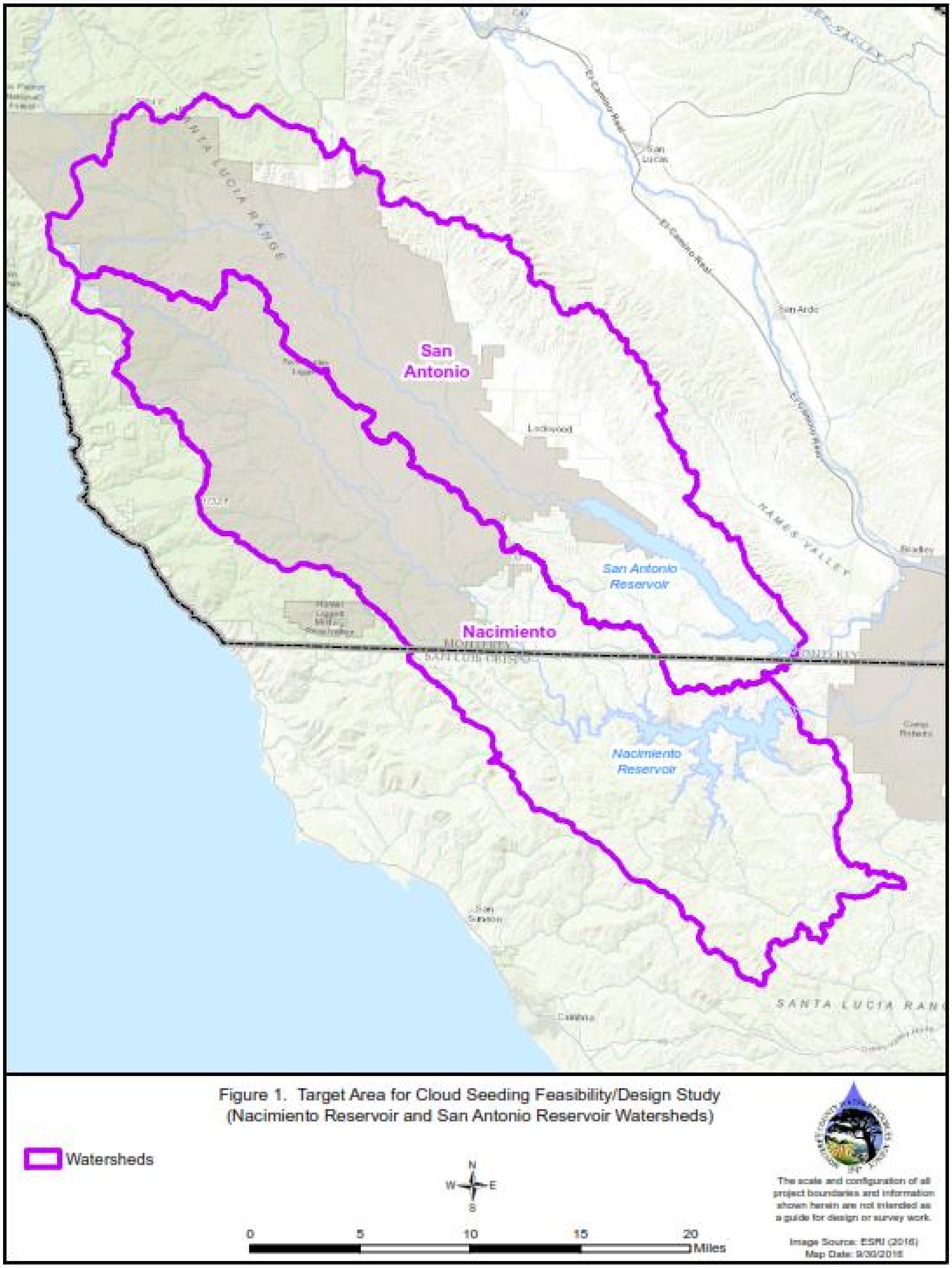

Figure 1.1 Locations of Proposed Target Areas

2.0 THEORY OF CLOUD SEEDING FOR PRECIPITATION AUGMENTATION

Clouds form when temperatures in the atmosphere reach saturation, that is, relative humidities of 100%. This saturated condition causes water vapor to condense around a nucleus forming a cloud droplet. These nuclei, which may be small particles like salts formed through evaporation off the oceans, are known as "cloud condensation nuclei." Clouds can be composed of water droplets, ice crystals or a combination of the two. Clouds that are entirely warmer than freezing are sometimes referred to as "warm clouds." Likewise, clouds that are colder than freezing are sometimes referred to as "cold clouds." Cold clouds may have cloud bases that are warmer than freezing. Precipitation can occur naturally from both types of clouds.

In warm clouds, cloud droplets that survive long enough and especially when cloud drops are of different sizes, may result in cloud water droplets colliding and growing that may reach raindrop sizes that can fall to the ground as rain. This process is known as "collision/coalescence." This process is especially important in tropical clouds but can also occur in more temperate climates.

In cold regions (< 0°C) of clouds, cloud water droplets may not freeze. The reason for this is the purity of the cloud water droplets. In a laboratory environment, pure water droplets can remain unfrozen down to a temperature of -39°C. Natural impurities in the atmosphere can cause cloud droplets that are colder than freezing (usually referred to as supercooled) to freeze. These supercooled cloud droplets are what causes icing to occur on aircraft. The natural impurities often consist of tiny soil particles or bacteria. These impurities are referred as "freezing nuclei." A supercooled cloud droplet can be frozen when it collides with one of these natural freezing nuclei thus forming an ice crystal. This process is known as "contact nucleation." A water droplet may also be formed on a freezing nucleus, which has hygroscopic (water attracting) characteristics. This same nucleus can then cause the water droplet to freeze at temperatures less than about -5°C forming an ice crystal. This process is known as "condensation/freezing." Once an ice crystal is formed within a cloud it will grow as cloud droplets around it evaporate and add their mass to the ice crystal eventually forming a snowflake (diffusional growth). Ice crystals can also gain mass as they fall and contact then freeze other supercooled cloud droplets, a process known as "riming." These snowflakes may fall to ground as snow if temperatures at the surface are ~ 0°C or colder. They may reach the surface as raindrops if surface temperatures are warmer than freezing.

Research conducted in the late 1940's demonstrated that tiny particles of silver iodide could mimic Mother Nature and serve as freezing nuclei at temperatures colder than about -5°C. In fact, these silver iodide particles were shown to be much more active at temperatures of ~ -5° to -15°C than the natural freezing nuclei found in the atmosphere. As a consequence most of man's modern day attempts to modify clouds to produce more precipitation (or reduce hail) have used silver iodide as a seeding agent. By definition, these programs are conducted to affect colder portions of clouds; typically cloud regions that are -5°C or colder (e.g., "cold clouds"). These programs are sometimes called cold cloud or glaciogenic seeding programs. Glaciogenic cloud seeding can be conducted in summertime clouds by seeding clouds whose tops pass through the -5°C level and winter stratiform clouds that reach at least the -5°C level.

There have been some research and operational programs designed to increase precipitation from "warm clouds." The seeding agents used in these programs are hygroscopic (water attracting) particles typically some kind of salt (e.g., calcium chloride). These salt particles can form additional cloud droplets, which may add to the rainfall reaching the ground. This seeding technique which is sometimes referred to as warm cloud or hygroscopic seeding can also modify the warm portion of clouds that then grow to reach temperatures colder than freezing. A research program conducted in South Africa targeting these types of clouds indicated that such seeding did increase the amount of rainfall from the seeded clouds.

In summary, most present day cloud seeding programs introduce a seeding agent, such as microscopic sized silver iodide particles, into clouds whose temperatures are colder than freezing. These silver iodide particles can cause condensation forming cloud droplets that subsequently freeze or cause naturally occurring cloud droplets to freeze forming ice crystals. These ice crystals can grow to snowflake sizes falling to the ground as snow or as rain depending on whether the surface temperature is below or above freezing.

3.0 REVIEW AND SUMMARY OF RELEVANT PRIOR STUDIES AND RESEARCH

3.1 Santa Barbara II Research Program

The Santa Barbara II research program (1967-1974) consisted of two primary phases. Phase I consisted of the release of silver iodide from a ground location near 2,500 feet MSL located in the Santa Ynez Mountains northwest of Santa Barbara. These silver iodide releases were made as “convective bands” passed overhead. The releases were conducted on a random seed or no-seed decision basis in order to obtain baseline non-seeded (natural) information for comparison. A large network of recording precipitation gauges were installed for the research program (Figure 3.1). The amount of precipitation that fell from each seeded or non-seeded convective band was determined at each precipitation gauge location. Average convective band precipitation for seeded and non-seeded events was calculated for each rain gauge location. Figure 3.2 shows the results of seeding from the ground as contours of the ratios of average seeded band precipitation versus the non-seeded band precipitation.

Ratios greater than 1.0 are common in Figure 3.2. A ratio of 1.50 would suggest a 50 percent increase in precipitation from seeded convective bands compared to non-seeded bands. The high ratios in southwestern Kern County are not significant in terms of amounts of additional rainfall since the convective bands (both seeded and non-seeded) rapidly lose intensity as they enter the San Joaquin Valley. In other words, a high percentage applied to a low base amount does not yield much additional precipitation. These apparent effects may be due to delayed ice nucleation which would be expected with the type of seeding flares used in this experiment that operated by contact nucleation which is a relatively slow process.

The low amounts of natural precipitation in southwest Kern County results from evaporation in “downslope” flow in the winter storms that affect this area. Such predominant “downslope flow” areas are frequently known as rain-shadow areas in the lee of mountain ranges. The 1.5 ratios along the backbone of the Santa Ynez Mountains are, however, significant in terms of rainfall amounts since this area receives higher natural precipitation during winter storms due to “upslope” flow. This upslope flow is also known as an orographic effect and accounts for many mountainous areas in the west receiving more precipitation than adjoining valleys (especially downwind valleys). It was concluded that convective band precipitation was increased over a large area using this ground seeding approach.

In a similar experiment, Santa Barbara II, phase II, an aircraft was used to release silver iodide (generated by silver iodide - acetone wing tip generators) into the convective bands as they approached the Santa Barbara County coastline west of Vandenberg Air Force Base. The convective bands to be seeded were also randomly selected. Figure 3.3 provides the results of this experiment. Again, a large area of higher precipitation is indicated in seeded convective bands compared to non-seeded convective bands. Notice the westward shift of the effect in this experiment versus the ground-based experiment. This feature is physically plausible since the aircraft seeding was normally conducted off the coastline in the vicinity of Vandenberg AFB (i.e., west of the ground-based release point).

A study of the contribution of "convective band" precipitation to the total winter precipitation in the Santa Barbara County and surrounding areas was conducted (in the analysis of the Santa Barbara II research program). This study indicated that convective bands contributed approximately one-half of the total winter precipitation in this area (Figure 3.4). If it is assumed that all convective bands could be seeded in a given winter season and that a 50 percent increase was produced, the result would be a 25 percent increase in winter season precipitation if we assume the convective bands would have contributed one half of the winter season's rainfall. The two reports mentioned earlier (Thompson **et al.**, 1988 and Solak **et al.**, 1996) provided a more precise quantification of the optimal seeding increases that might be expected at Juncal and Gibraltar Dams (i.e., 18-22%) from seeding convective bands.

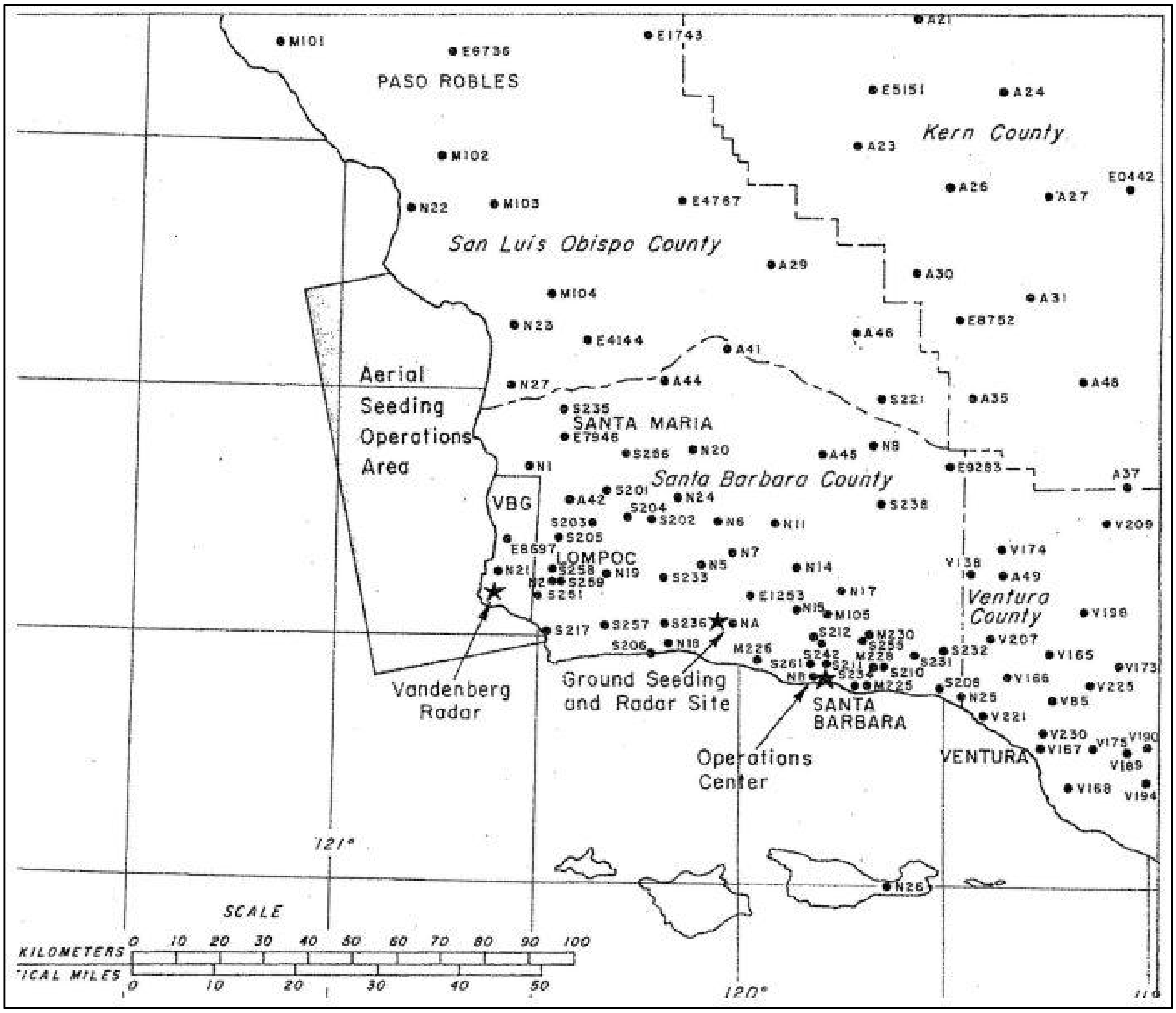

Figure 3.1 Santa Barbara II project map showing rain gauge locations, radar, and seeding sites.

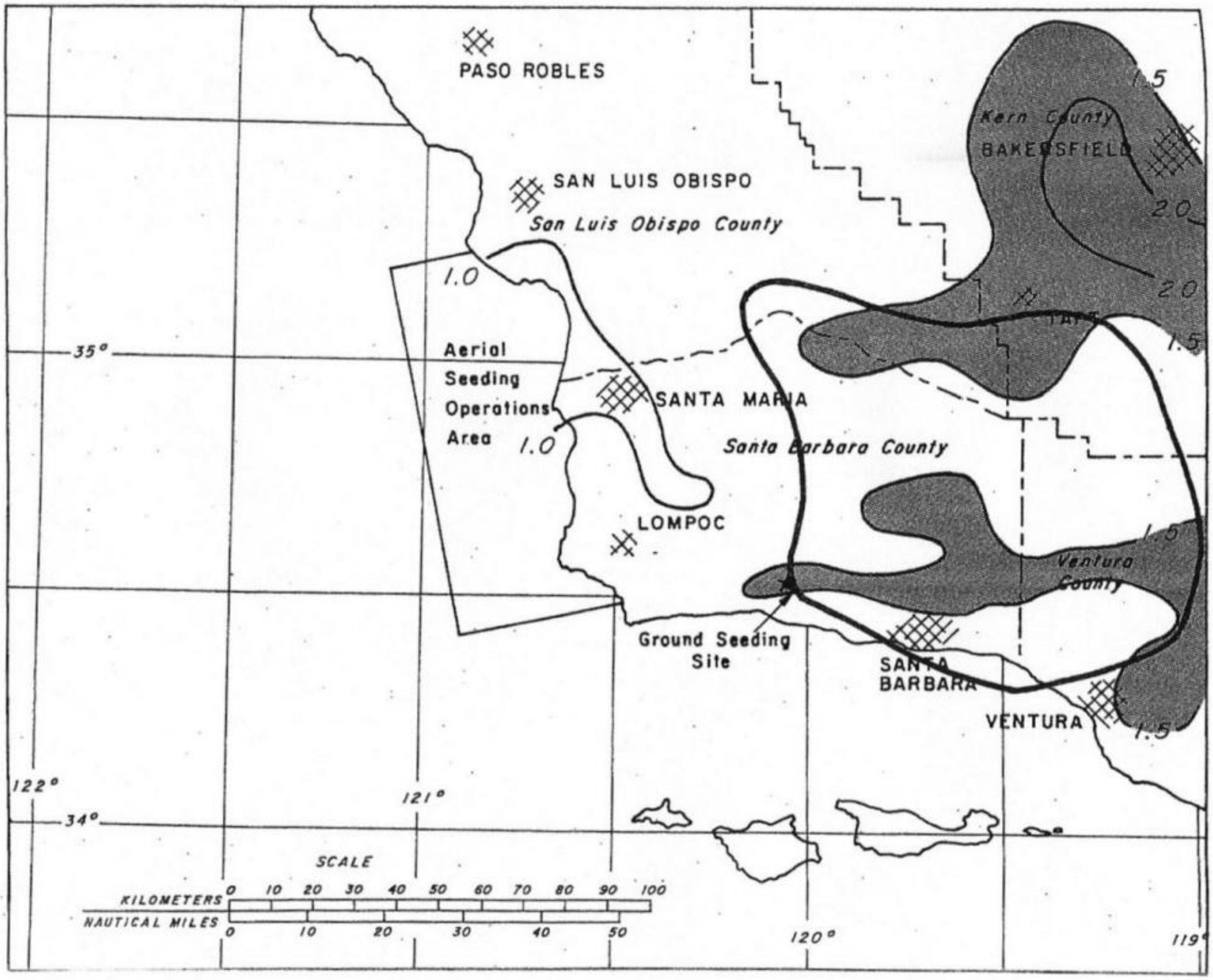

Figure 3.2 **Seeded/not-seeded ratios of band precipitation for Phase I ground operations, 1967-71 seasons; 56 seeded and 51 not-seeded bands.**

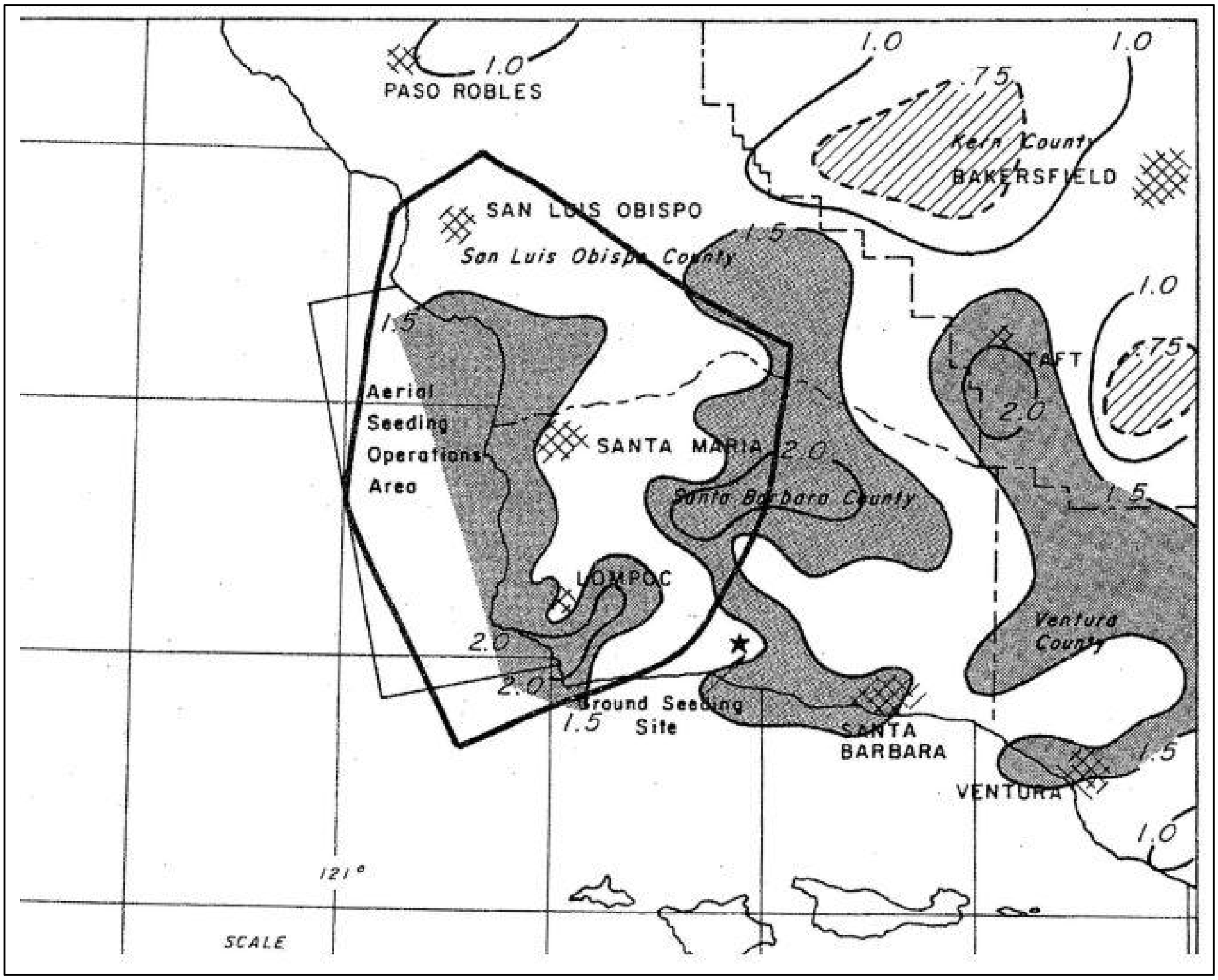

Figure 3.3 Seeded/not-seeded ratios of band precipitation for Phase II aerial operations, 1970-74 seasons; 18 seeded and 27 not-seeded bands.

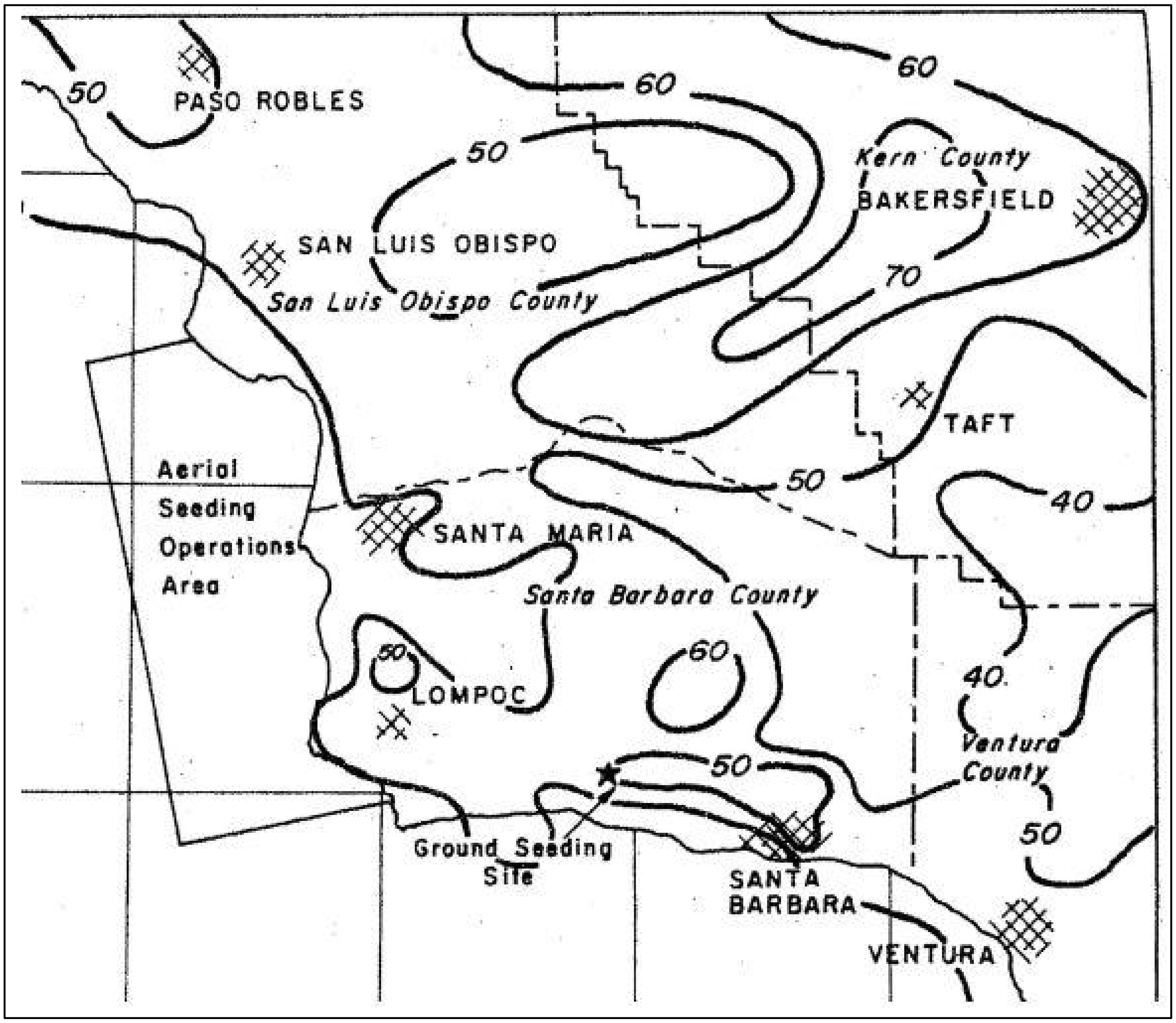

Figure 3.4 Approximate percentage of winter precipitation occurring in convective bands, 1970-74 seasons

For illustration purposes, Figure 3.5 provides a sequence of six radar images of a convective band as it moved into Santa Barbara County on April 11, 2010. The radar images are from the Vandenberg AFB NEXRAD radar site. Table 3-1 shows short duration rainfall values at Santa Maria during this event. Higher intensity rainfall occurred as the heart of the convective band moved over Santa Maria.

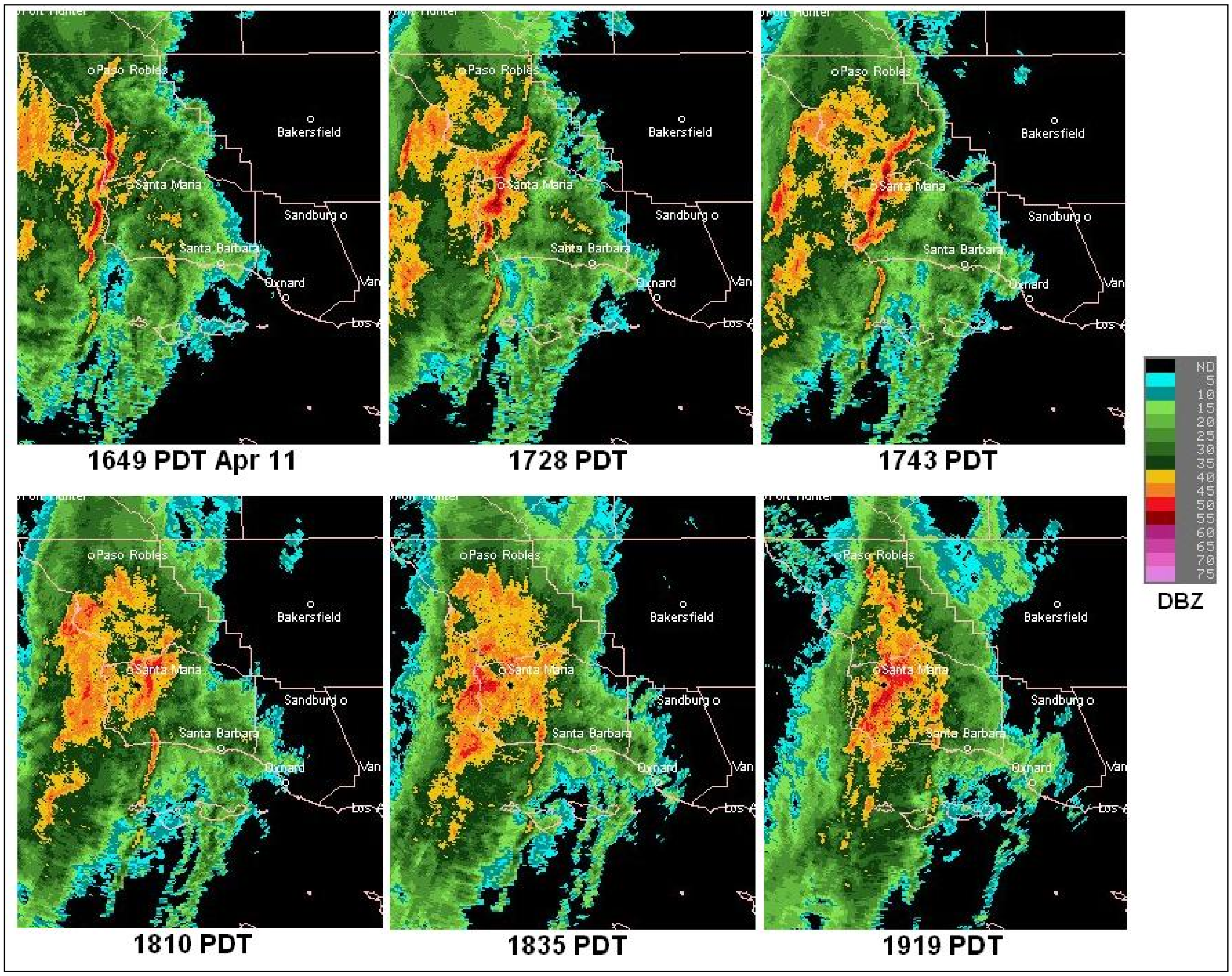

Figure 3.5 Convective band passing over western Santa Barbara County on April 11, 2010 as observed by the Vandenberg AFB NEXRAD Radar

Table 3-1 Short Duration Rainfall Amounts (inches) at the Santa Maria Airport during Storm Event in Figure 3.5

Time Period (PST)	1630 - 1700	1700 - 1730	1730 - 1800	1800 - 1830	1830 - 1900	1900 - 1930	1930 - 2000
Precipitation (in)	0.03	0.26	0.35	0.12	0.10	0.12	0.02

More recent research conducted in Texas (Rosenfeld and Woodley, 1993; Rosenfeld and Woodley, 1997) and in Thailand (Woodley and Rosenfeld, 1999) has also indicated additional rainfall being produced from silver iodide seeding of convective cloud elements. These increases appear to occur due to increased duration of the seeded entities rather than increases in precipitation intensity. These indications are in agreement with the results observed in the Santa Barbara II research program.

In summary, earlier research conducted in Santa Barbara County indicated that convective bands are a common feature of winter storms that impact Santa Barbara County and that those bands contribute a significant proportion of the area precipitation. In addition, research has indicated that these bands contain supercooled liquid water droplets; the target of most modern day cloud seeding activities (Elliott, 1962). Seeding these bands with silver iodide either from the ground or air increases the amount of precipitation received at the ground. These bands are typically oriented in some north to south fashion (e.g. northeast to southwest, northwest to southeast, etc.) as they move from west to east. It is common to have at least one convective band per winter storm with as many as three or four per storm being fairly common. One band is usually associated with cold fronts as they pass through the county. Frequently these frontal bands are the strongest, longest lasting bands during the passage of a storm. Other bands may occur in either pre-frontal or post-frontal situations. The duration of these bands over a fixed location on the ground can vary from less than one hour to several hours duration.

In 2013 the Santa Barbara County Water Agency asked NAWC if there was some method that could be employed to estimate the cloud seeding effects of an operational winter program that had been conducted most winters in Santa Barbara County since 1981. There have typically been two target areas in this program: the Upper Santa Ynez drainage above Cachuma Dam located in the eastern part of Santa Barbara County, and the Twitchell Reservoir drainage (sometimes referred to as the Huasna-Alamo target area) located in the northern portion of Santa Barbara County and the southern portion of San Luis Obispo County. This operational program was implemented in water year 1986 following the completion of the Santa Barbara II research program which provided indications of positive seeding effects from seeding convective bands, some of which were statistically significant.

North American Weather Consultants (NAWC) performed an historical target/control analysis of this program for the Santa Barbara County Water Agency in 2013, which had not been attempted previously. A search for potential long-term target and control precipitation measurement sites was conducted which identified three acceptable control sites and four acceptable target sites (two in each of the intended target areas). Figure 3.6 provides these locations. Linear and multiple-linear regression equations were developed for each of the target areas using periods without any cloud seeding in either the control or target areas. Relatively high correlations were obtained between the control and target sites with r^2 values ranging from 0.84 to 0.91 (Griffith, et al, 2015).

When these regression equations were used to predict the amount of natural precipitation for the December-March period for the two target areas during seeded seasons and then compared to the actual amounts of precipitation, the average results for all the seeded seasons were:

- Upper Santa Ynez Target Area: Estimated increases of 19% to 21% from the linear and multiple-linear equations (24 seeded seasons).

- Huasna-Alamo Target Area: Estimated increases of 9% from both the linear and multiple-linear equations (27 seeded seasons).

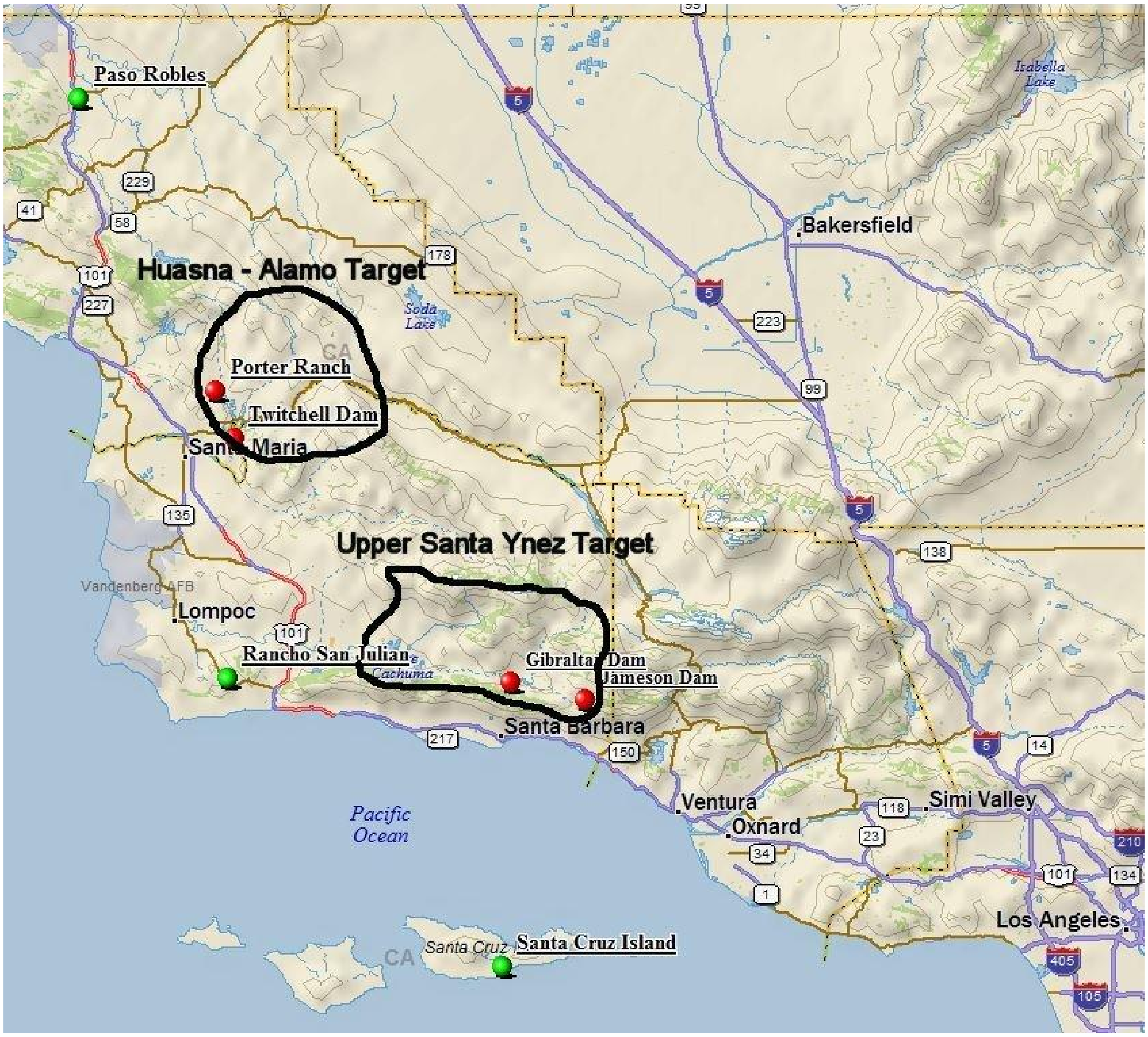

Figure 3.6 **Map of the two Cloud Seeding Target Areas and the Locations of Precipitation Control Sites (green) and Target Sites (red).**

3.2 Snowy Mountains Precipitation Enhancement Research Project

Another winter orographic ground based seeding research program of relevance was recently completed in the Snowy Mountains of Australia (Manton, et al, 2011 and Manton and Warren, 2011). The following is the abstract taken from the second paper:

> *"The Snowy Mountains Precipitation Enhancement Research Project (SPERP) was undertaken in winters from May 2005 to June 2009 in the Snowy Mountain region of southeastern Australia. Part I of this paper describes the design and implementation of the project, as well as the characteristics of the key datasets collected during the field phase. The primary analysis in this paper (Part II) shows an unequivocal impact on the targeting of seeding material, with the maximum level of silver in snow samples collected from the primary target area found to be significantly greater in seeded than unseeded experimental units (EUs). A positive but not statistically significant impact on precipitation was found. Further analysis shows that a substantial source of uncertainty in the estimation of the impacts of seeding on precipitation is associated with EUs where the seeding generators operated for relatively few hours. When the analysis is repeated using only EUs with more than 45 generator hours, the increase in precipitation in the primary target area is 14% at the 8% significance level. When applying that analysis to the overall target area, the precipitation increase is 14% at the 3% significance level. A secondary analysis of the ratio of silver to indium in snow supports the hypothesis that seeding material affected the cloud microphysics. Other secondary analyses reveal that seeding had an impact on virtually all of the physical variables examined in a manner consistent with the seeding hypothesis."*

3.3 Wyoming Weather Modification Pilot Program (WWMPP)

Yet another multi-year winter orographic seeding research program recently was completed. This program was conducted in the Sierra Madre and Medicine Bow Ranges located in south central Wyoming (Breed, et al, 2014). The following was taken from a draft executive summary of an analysis of the results obtained from this experiment (NCAR, 2014).

The WWMPP provided an assessment of weather modification as a strategy for long-term water management. Specifically, the project was funded to determine whether seeding in Wyoming is a viable technology to augment existing water supplies, and if so, by how much, and at what cost.

The physical evidence from radiometer measurements showed that ample supercooled liquid water existed at temperatures conducive to generating additional snow by silver iodide seeding over the ranges studied. High-resolution and quality-controlled snow gauges were critical to evaluate the effectiveness of cloud seeding and validate the performance of the model used during the WWMPP.

The accumulation of evidence from statistical, physical, and modeling analysis suggests that cloud seeding is a viable technology to augment existing water supplies, for the Medicine Bow and Sierra Madre Ranges. While the primary statistical analysis did not show a significant impact of seeding, statistical analysis stratified by generator hours showed increases of 3-17% for seeded storms. A climatology study based on high-resolution model data showed that ~30% of the winter time precipitation over the Medicine Bow and Sierra Madre Ranges fell from storms that met the WWMPP seeding criteria. Ground-based silver iodide measurements indicated that ground-based seeding reached the intended target, and in some cases well downwind of the target. High-resolution modeling studies by NCAR that simulated half of the total number of seeding cases showed positive seeding effects between 10-15% for the seeded test cases. When these indicated results were compiled for possible seasonal estimates of seeding increases the results were 1.5 to 5% increases.

4.0 REVIEW AND ANALYSIS OF THE CLIMATOLOGY OF THE PROPOSED TARGET AREAS

Central portions of coastal California have a Mediterranean type of climate in general, with warm dry summers and wet winters in most areas. The Lake Nacimiento drainage lies in the inland northern portion of San Luis Obispo County and the inland southern portion of Monterey County, with a semi-arid climate over much of the area and higher precipitation in some mountain locations. Precipitation data were available for several stations in this area. Overall, November through April estimates ranged from just over 10 inches to over 36 inches with King City being the driest and Big Sur the wettest. The majority of the sites have averages between 11-18 inches for the November – April period, which is likely a good estimate for these watersheds in the feasibility study as a whole.

Analysis of the monthly precipitation climatology was conducted using 10 stations in Monterey and northern San Luis Obispo counties with long-term records that date back, in a couple cases to at least the 1910s. The seasonal distribution at these sites should be similar to the Lake Nacimiento and Lake San Antonio drainages where only sparse data was available. The multi-station average in Figure 4.1 shows a bi-monthly peak in January-February (20.58% January, 20.64% February). The November – April period accounted for approximately 93% of the annual precipitation in this composite plot, with the shorter December – March seasonal period accounting for slightly over 75% of the annual total. Dividing the totals for the two periods shows that the December – March season accounts for about 81% of the November – April totals. For the Lake Nacimiento watershed, this means December – March precipitation totals ranging from about 8-9 inches in some of the driest areas to 29 inches in the wetter, higher elevation areas. While the magnitude of observed precipitation varies considerably from one location to another, the distribution shown in Figure 4.1 should be relatively consistent across the area.

The proposed target area climatology in terms of seedable events is believed to be fairly similar to the Santa Barbara County seeding target areas for which seeding results were originally examined in terms of the meteorological conditions and frequency of convective band passages. An analysis of convective band passages over a five-year period in northern San Luis

Obispo County and southern/central Monterey County was conducted in order to classify the temperature and wind characteristics of these bands. Table 4-1 shows the 700 mb (approximately 10,000 feet) data estimates that were obtained. Figure 4.2 is a wind direction frequency plot for these events.

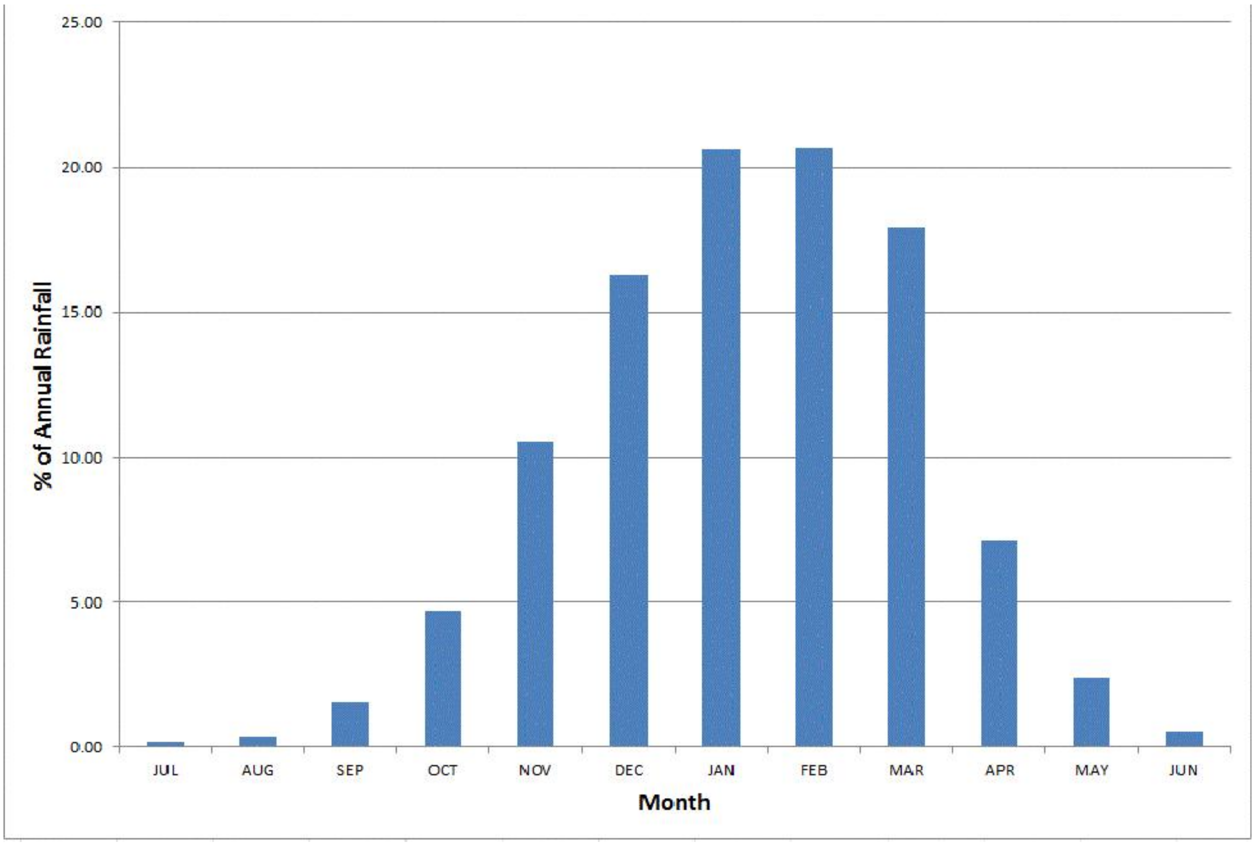

Figure 4.1 Monthly Precipitation Climatology for Monterey and northern San Luis Obispo counties, Percent of Annual Total.

Table 4-1

Convective Band Passage Times and Characteristics, Water Years 2010-2015

Date	Time (PST)	700 mb max T (°C)	700 mb min T (°C)	Wind speed (kts)	Wind direction range	Wind direction average
12/5/2010	1800-2200	-2	-2	30-40	180-210	195
12/25/2010	1600-2100	-2	-4	35-45	180-220	200
1/2/2011	0100-0500	-6	-7	30-40	220-240	230
2/16/2011	0200-0600	-6	-8	35-45	240-270	255
2/18/2011	1100-1600	-6	-6	40-50	220-240	230
3/19/2011	2000-2300	-5	-7	35-45	240-260	250
3/20/2011	0100-0700	-3	-4	30-40	230-240	235
3/23/2011	0800-1300	-4	-7	30-40	250-280	265
1/20-21/2012	2300-0300	1	1	45-55	260-280	270
1/23/2012	0300-0600	-3	-5	40-50	250-270	260
3/17/2012	0100-0400	-3	-5	40-50	240-260	250
3/25/2012	0100-0400	-3	-6	40-50	200-230	215
4/13/2012	0400-0700	-8	-9	40-50	230-270	250
12/22/2012	0200-0800	-3	-4	35-45	240-260	250
12/25-26/2012	2100-0000	-2	-4	35-45	260-280	270
2/19/2013	1400-1600	-8	-10	30-40	250-270	260
3/7/2013	1900-2300	-9	-10	20-30	220-240	230
2/2/2014	1100-1300	-7	-9	15-25	260-280	270
2/26/2014	1600-2000	-1	-3	40-50	240-260	250
3/1/2014	1000-1300	-6	-6	30-40	220-240	230
3/31/2014	1600-1900	-6	-10	30-40	250-270	260
12/11-12/2014	2100-0100	-4	-7	40-50	220-240	230
12/16-17/2014	2000-0000	-5	-7	20-30	250-270	260
2/6-7/2015	2300-0300	1	3	40-50	240-250	245
3/1/2015	1500-1700	-9	-10	10-20	180-220	200
4/7/2015	0800-1100	-5	-7	30-40	250-270	260

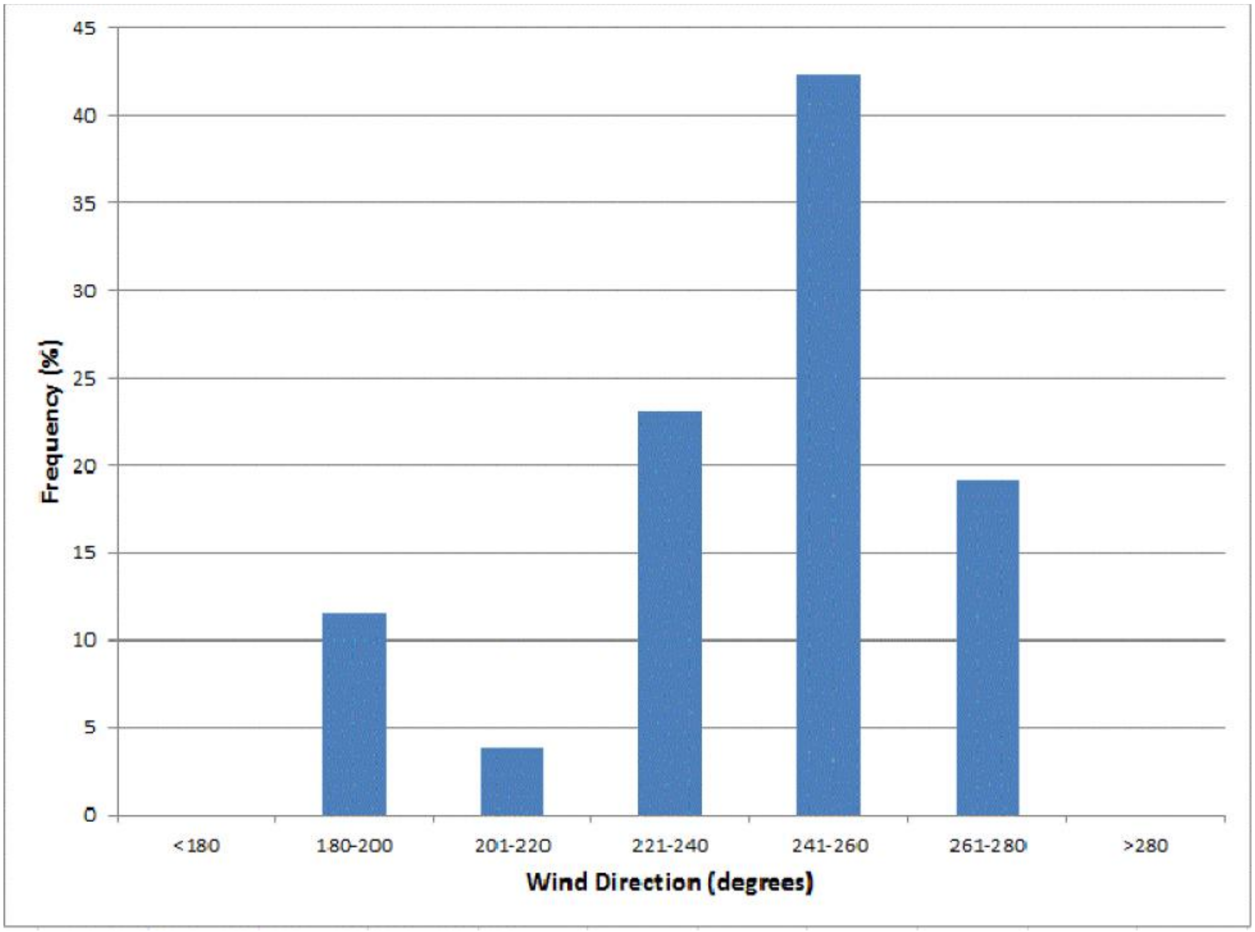

Figure 4.2 700 mb Wind Direction Frequency Plot during Convective Band Passages

Further breakdown of the convective band 700 mb data (estimates) shows that the 700 mb temperature averaged about -4.4°C during the early portion of a frontal convective band passage and around -5.9°C in the latter portion of the band passages, resulting in an overall average of a little colder than -5.1°C for the events in Table 4-1. This implies a typical -5°C level between 9,000 and 10,000 feet MSL. On the cold end of the spectrum, 700 mb temperatures in the -10° to -12°C range will typically bring the -5°C level down to near 6,000 feet MSL during a significant precipitation period. On the warmer end, 700 mb temperatures around 0°C are typically associated with a -5°C level around 12,000 to 13,000 feet MSL, and occasionally higher if there is some mid-level thermodynamic stability involved as with some cases of tropical/subtropical moisture plumes. The height of the -5°C level is important as discussed in Section 2 since silver iodide nuclei begin to activate near this temperature. This means that silver iodide seeding material released from ground sites must rise to this level in order to begin the artificial augmentation of precipitation. The generalized seeding criteria in Table 5-4 indicate that NAWC typically considers ground-based seeding operations in this area to be effective if the 700 mb temperature is -5°C or colder. Temperatures when using seeding aircraft are not as restrictive since the aircraft can be flown at higher altitudes in warmer storms (e.g., flight levels at the -5°C level).

Another consideration is monthly temperature distributions during storm events. Overall, early season (December – January) storms in the analysis were somewhat warmer (-3.6°C average 700 mb temperature) than late season (March – April) events which averaged -6.5°C at 700 mb. This concurs with some past analyses in other areas of California which indicate coldest storm period temperatures and lowest snow levels in general occur during March and April. The 700 mb wind speeds in the analyzed band passages also averaged higher during the early season (39.4 knots) compared to the later events (35.5 knots). This, combined with generally better atmospheric mixing during the spring due to a higher sun angle implies that more favorable seeding conditions are generally more likely during late season storm events. Near the end of the season (i.e., second half of April) synoptic-scale systems tend to transition from open-wave frontal systems with distinct band passages to, more commonly, closed-low types of systems which may present more disorganized convective and more variable wind patterns (e.g., easterly component). This becomes a negative factor late in the season when trying to target convective band passages to impact the target areas especially when using ground-based generators which are typically sited taking prevailing wind directions into account.

Weighing the above factors, a four-month seeding program during a December – March (or mid-December through mid-April) time frame would probably be the most favorable. A five-month period of November 15th – April 15th would be a potentially good option, as would a more inclusive six-month period of November – April. From past experience with seeding programs in California, many November events are quite warm and may not present distinct convective frontal band passages at the latitude of Lake Nacimiento/Lake San Antonio, thus November may be the least favorable of this six-month period in general.

5.0 DEVELOPMENT OF A PROGRAM DESIGN

5.1 Technical Program Design

It is NAWC's philosophy that the design of operational programs should be based upon prior research programs that provided positive indications of increases in precipitation, to the extent that the research results are considered representative of the operational programs' conditions (i.e., transferable results). The proposed program for the Nacimiento Reservoir and San Antonio Reservoir drainages (NRSAR) has a unique advantage in this regard since a well-funded winter research program Santa Barbara II, Phases I and II was conducted during the winters of 1967-1973. Section 3.1 discusses the results of this research program, which were very positive. Furthermore, there have been operational seeding programs conducted most winter seasons since 1981 targeting the Twitchell and Upper Santa Ynez drainages in Santa Barbara and southern San Luis Obispo Counties. The design of these programs since the early 2000's has been based upon the design used in the conduct of the Santa Barbara II research program. A recent peer reviewed evaluation of this operational program provided estimated results from seeding ranging from 9 to 21% (Griffith, et al, 2015).

Even though the Santa Barbara II research program was conducted approximately 40 years ago, it is our professional opinion that it offers the most relevant information for the design of precipitation enhancement programs for this area at the present time. There has not been any winter weather modification research conducted in representative coastal areas of the United States since Santa Barbara II. **This is a prime example of technology transfer from research to operations. We believe the best project design for a winter cloud seeding program in the NRSAR is one that duplicates, as much as possible, the design of the Santa Barbara II research program. In fact, the combination of Phase I and II seeding modes (ground and airborne) should optimize the seeding potential for the area. Our design is based upon this approach.** More details regarding the proposed design are provided in a categorical fashion in the following sections.

The recommended operational five-month period would be November 15th through April 15th each winter season. From a climatology analysis done for the county, the vast majority of the annual precipitation in this area occurs during this five-month period. A base program is recommended that would involve the siting, installation and operation of three or four ground-based remotely operated flare tree units. These units are known as Automated High Output Ground Seeding Systems (AHOGS). Figure 5.1 provides a photo of a site being used on the current Santa Barbara winter seeding program. Section 5.9 provides some potential sites based upon some HYSPLIT modeling runs. Follow-on site surveys would be needed to determine the utility of these sites which are beyond the scope of this study. Land ownership will also need to be considered. The Santa Barbara County Water Agency arranges annual leases for the six sites used on the Twitchell and Upper Santa Ynez drainage programs.

A cloud seeding aircraft could be added to augment (perhaps for a three or four-month period) the recommended base program using ground-based flare units. Nearly 75% of the annual precipitation for Monterey County occurs during the December 1 to March 31 period. There may be the potential to share the utilization of seeding aircraft like ones that the Santa Barbara County Water Agency has often included in their programs for the Twitchell and Upper Santa Ynez drainage target areas. This may be feasible since the targeted clouds are convective bands that tend to first impact Monterey County then Santa Barbara County. In other words, a seeding aircraft may be able to travel with bands as they move through one or both of the Water Agencies target areas. Figure 5.2 provides a photo of a Cheyenne II cloud seeding aircraft used in Santa Barbara County during recent winter seasons. This seeding aircraft uses the same silver iodide flares as used in the ground-based sites.

Figure 5.1 West Camino Cielo AHOGS Site

Figure 5.2 Cheyenne II Cloud Seeding Aircraft with End Burning Flare Racks

5.2 Personnel

Depending upon the seeding mode (i.e., ground based flares, aircraft seeding) or modes used there may be the following staff positions: 1) a program supervisor, 2) a program meteorologist, 3) a pilot, and 4) a local part time technician. The supervisor and meteorologist could operate from the contractor's headquarters. The pilot would be stationed at a suitable airport in proximity to the target area. NAWC recommends that a Weather Modification Association (WMA) Certified Manager be the program manager and that a WMA Certified Operator serve as the program meteorologist.

The program meteorologist will perform the various project duties needed to conduct a safe and effective operation. A partial list of these duties is provided in Table 5-1.

Table 5-1

Partial List of Duties to be Performed by Program Meteorologist

1)	Monitor weather conditions and determine, based on meteorological data and radar observation, the approach of seedable storm systems.
2)	Estimate the probable results and impacts of seeding using predictive computer models, real time rain and river flow data from the Automated Local Evaluation in Real Time (ALERT) System, and other information. Such estimates shall be updated regularly as conditions change.
3)	Coordinate with MCWRA personnel to determine potential flows in key water courses and determine the appropriate action regarding seeding activities.
4)	Direct the actual seeding operations using appropriate storm selection and target area criteria and continuously monitor air and ground seeding operations using radar and remote interrogation systems.
5)	Maintain constant and continuous control over all air and ground seeding devices and keep an accurate written or digital log of the time that each and every generator is activated and deactivated (flare fire times) and in the case of aerial seeding, aircraft position.
6)	Inform MCWRA personnel, through prescribed communication channels and in a timely manner, of all significant events relative to the program, including beginning and ending seed times.
7)	Provide necessary radar and precipitation data to MCWRA staff as requested during periods of heavy rainfall or flooding.
8)	Determine when conditions are such that program operations should be suspended for any weather related reason and adhere to suspension criteria designed by the MCWRA prior to project initiation.
9)	Maintain, and submit copies of written operations reports to the MCWRA in a timely manner. At a minimum, such reports shall be submitted subsequent to each seeding event and should involve a discussion of the above referenced items (see Communications for final report requirements).

If a seeding aircraft is part of the program, a licensed and instrument-rated pilot qualified to fly weather modification or similar weather and terrain demanding conditions should be available on a 30 minute notice during the aerial part of the project period. This pilot would need to meet the requirements imposed by aircraft insurance carriers, which can be rather stringent.

The combination of an experienced pilot with an experienced meteorologist provides a very workable situation. It is possible for aircraft operations to be directed from the Contractor's headquarters using a phone patch system that allows communications between the pilot and meteorologist during seeding flights. A specialized system known as Spidertracks can be mounted in the seeding aircraft, which provides frequently updated aircraft tracking information that can be displayed in the contractor's headquarters on a computer via the internet.

A local part time technician would provide technical support on an as-needed basis. For example, this technician could be responsible for the installation, recharging, maintenance and de-commissioning of the AHOGS sites. This technician could also provide support to the pilot if a seeding aircraft is utilized.

5.3 Weather Radar

Prior to 1992 weather radar information from the National Weather Service (NWS) was limited in the western United States. This situation changed dramatically when the NWS, through a modernization effort in the 1992-1997 period, installed a network of very sophisticated 10 cm weather radars throughout the U.S. These sites are known as NEXRAD (Next Generation Radar) installations. Each installation cost about $1,000,000. Figure 5.3 provides the array of these sites across the U.S. There are 160 NEXRAD sites now in service. NEXRAD radars provide information on precipitation intensities and wind speed and direction within the precipitation echoes. The radars step scan through 14 different elevation angles during approximately a 5 minute period, and a computer program integrates the stepped scans into a volume scan. Several very sophisticated algorithms then produce a large number of specialized displays and products from each volume scan. The maximum range for the detection of precipitation echoes is 143 miles from each site. The NWS provides all the necessary support for these systems; operation, calibration, spare parts and maintenance since the NEXRAD network is very important to NWS forecasting and public safety responsibilities, to many hydro-meteorological applications, and to aviation safety. Therefore, these radars enjoy high priority support and resultant reliability. The San Joaquin Valley and Vandenberg AFB NEXRAD radars would provide good coverage of the proposed NRSAR target area.

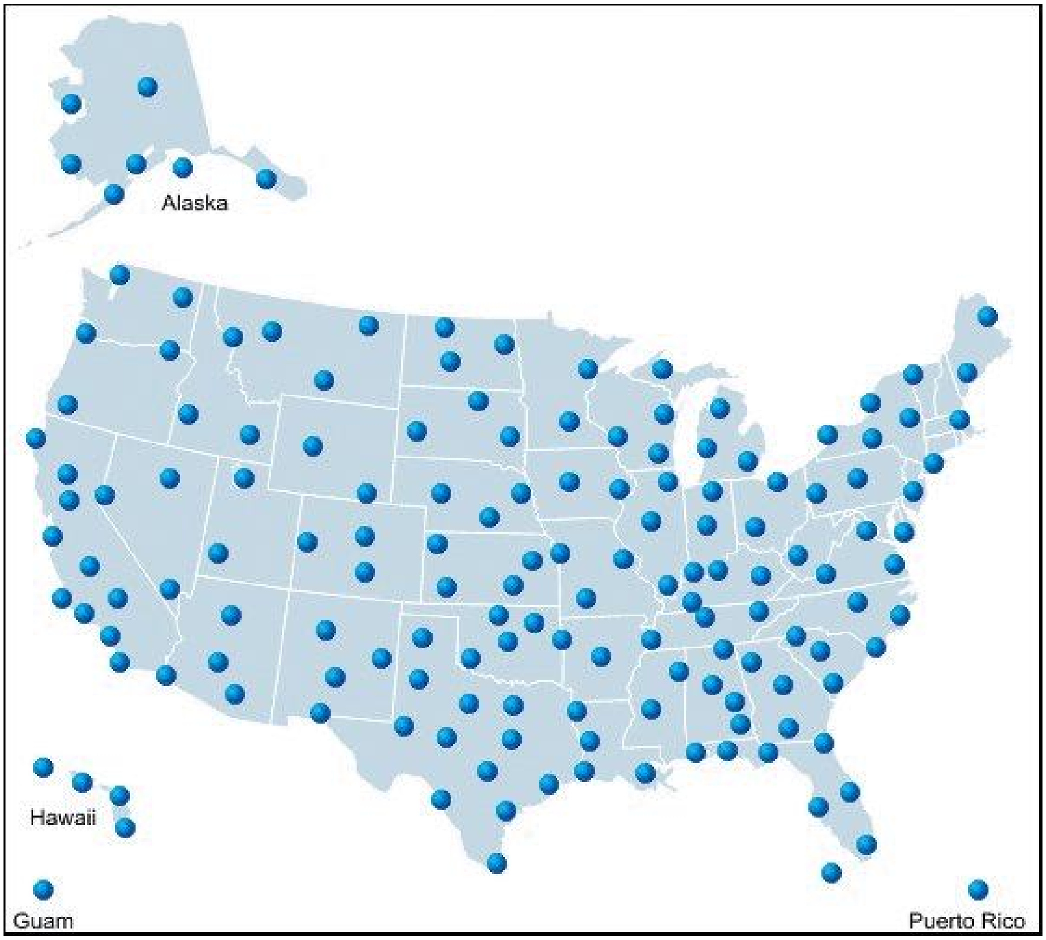

Figure 5.3 US NEXRAD radar locations

NEXRAD data are available online in near real time, at approximately 5-6 minute intervals. NAWC has utilized the WeatherTap (commercial, subscription) web site extensively over the past eleven years to provide radar data to conduct wintertime cloud seeding programs in Santa Barbara County. This web site provides a variety of useful products including: echo intensities (precipitation), echo tops, vertical distribution of wind speed and direction (the very useful VAD upper level wind displays), composite echo displays that integrate radar returns from all of the 14 different elevation scans. The Doppler wind capability provides rapid update (every six minutes) NEXRAD vertical azimuth display (VAD) wind profiles, which are invaluable in visualizing and identifying changes in the environmental wind fields that may affect seeding material and precipitation fallout trajectories. Figure 5.4 provides an example of VAD wind profiles for approximately a one hour period during a storm that impacted Santa Barbara County on February 26, 2014. This figure provides wind barbs at 1,000 foot intervals from 0340-0423 PDT. The wind direction is given by the direction the barbs are pointing. Lower-level winds during this period were blowing from the south in lower levels then veering to southwesterly above 5,000 feet. This is typical of a pre-frontal wind field during the passage of winter storms passing through Santa Barbara County. The strength of the wind is indicated by the number of flags on each barb. Typically, each barb represents a wind speed of 10 nautical miles per hour (knots), a short barb 5 nautical miles per hour. A triangular colored barb represents a value of 50 nautical miles per hour. For example, Figure 5.4 depicts wind speeds were around 20 knots at the 6,000 foot level.

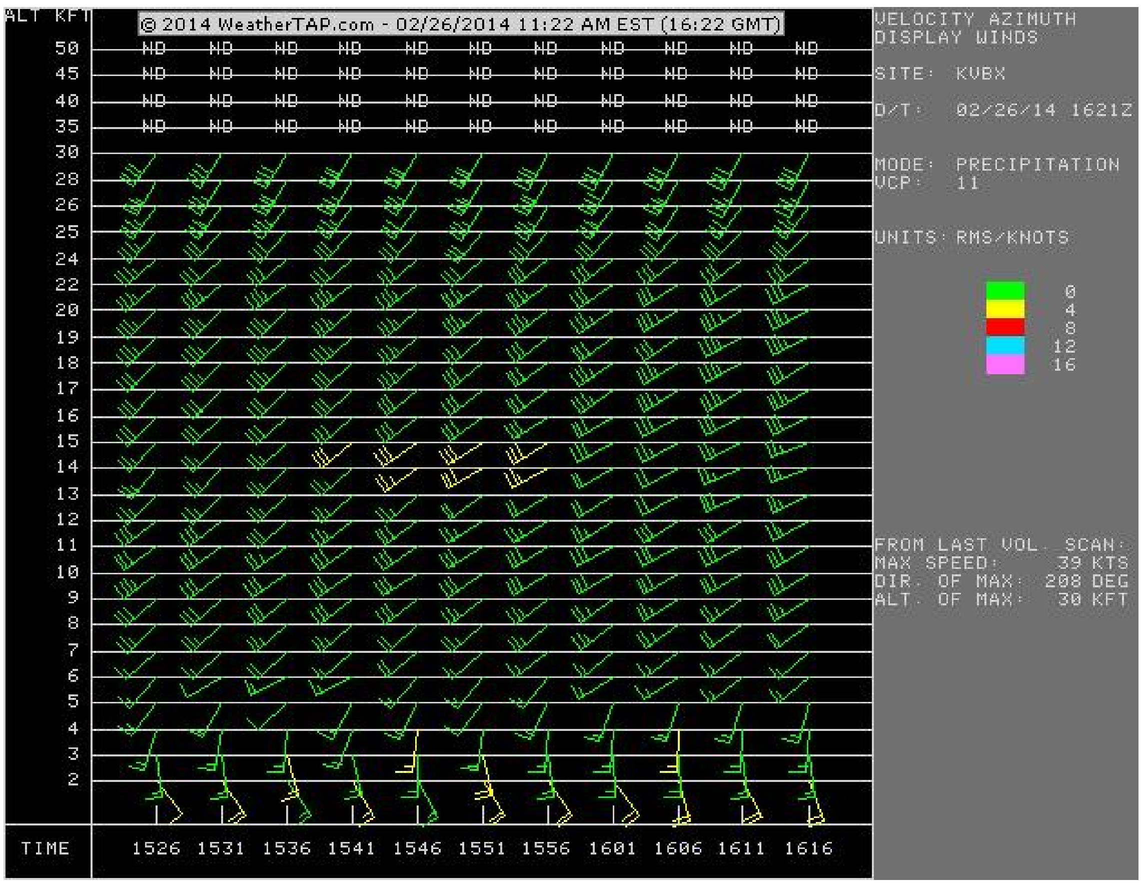

Figure 5.4 Vandenberg AFB Doppler winds, 0726-0816 PST, February 26, 2014

Figure 5.5 provides a Vandenberg Air Force Base NEXRAD radar image showing a convective band approaching Santa Barbara County at 1000 PST February 28, 2014. The different colors in this figure represent different radar reflectivity (dBZ) levels, which correspond to different rainfall rates. Utilization of NEXRAD data to conduct cloud seeding programs in the Santa Barbara area requires a separate provision of cloud seeding aircraft location and flight track information.

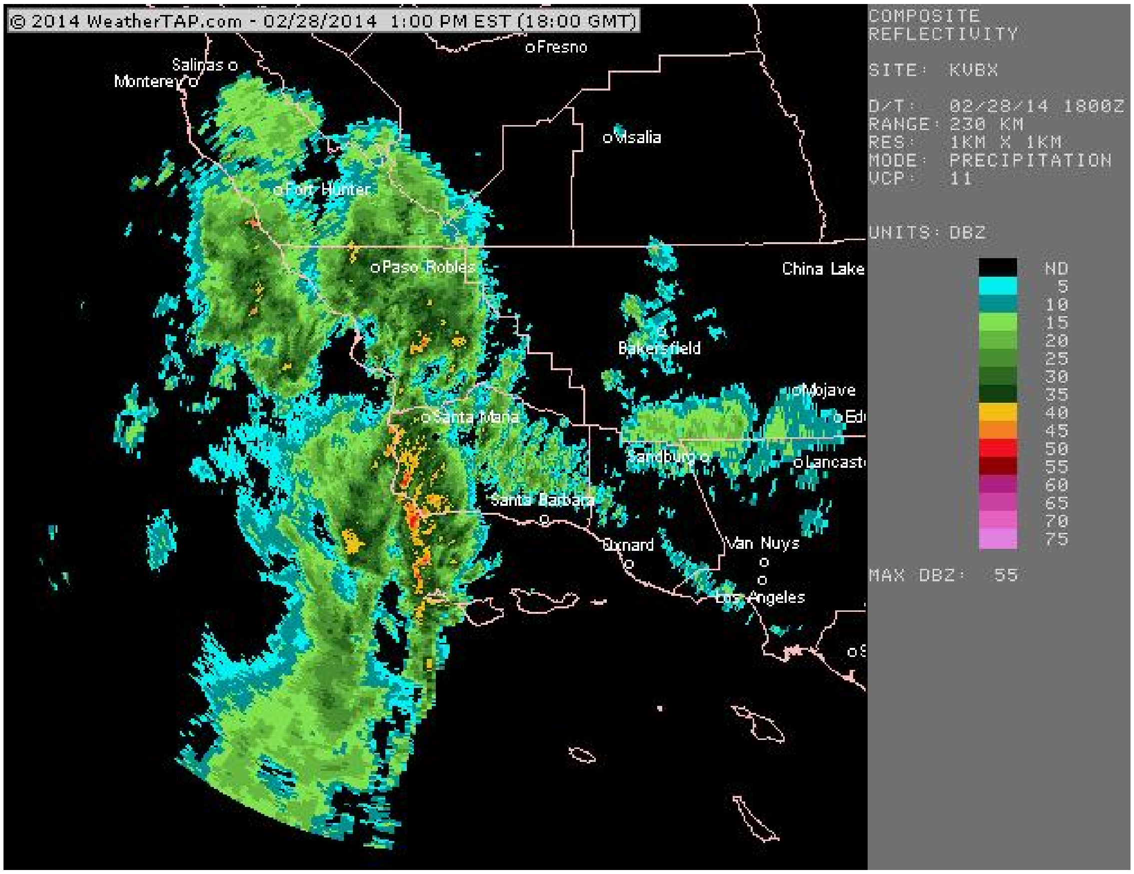

Figure 5.5 Vandenberg AFB radar image at 1000 PST on February 28, 2014

5.4 Ground Seeding Sites

NAWC developed a completely new design for remotely controlled ground based flare sites for the 2001-2002 Santa Barbara winter program (AHOGS - Automated High Output Ground Seeding System). This new design was used for the 2001-2016 programs with some upgrades over time. The AHOGS system allows automated, focused, high-output seeding releases from strategic ridgeline locations under program control from the project operations center with the proper computer software and password. These systems give the project meteorologist the ability to conduct intensive seeding of convective rain bands as they track into and across the project area under different wind flow regimes on a 24/7 basis. Each AHOGS consists of the following primary onsite components:

- Two flare masts, which hold a total of 32, 150-gram fast-acting silver iodide (AgI) flares.
- Spark arrestors that enclose each flare.
- An environmentally sealed control box containing a cellular phone communications system, digital firing sequence relays/controller, data logger and system battery.
- A solar panel/charge regulation system to maintain site power.
- Cellular phone antenna.
- Lightning protection.

Each site is controlled via a modem-equipped PC at the operations center, running custom software to manage the flare seeding operations. The meteorologist has the option of burning flares individually in real time, or to order batch burning of any number of flares at selectable intervals at each site, e.g., three flares at 15-min intervals, beginning at any selected time. The software allows monitoring and reporting of AHOGS site status information, such as flare inventory and battery voltage. These units do not require back up power since they each have their own DC battery that is recharged using a solar panel. These units have performed very reliably over the years of operations.

The same or similar system is proposed to be used on the NRSAR program. The siting, installation and operation of three or four sites is proposed. Approximate tentative locations are discussed in Section 5.9 based upon some HYSPLIT modeling studies.

Figure 5.6 shows a close-up of flares mounted in one of the masts. The original AHOGS design was modified for the 2005-2006 program through the introduction of a NAWC custom designed spark arrestor. These spark arrestors, which fit over each of the flares, were developed to assure no large sparks or burning embers were released from the flare burns that could pose a fire concern. Normally, this would not be a concern since flares are only burned when rain is occurring eliminating any fire danger. These arrestors were developed in case of an accidental misfire or burning flares at the beginning of a storm following an extended dry spell. Figure 5.7 provides a photo of a flare burning inside a spark arrestor.

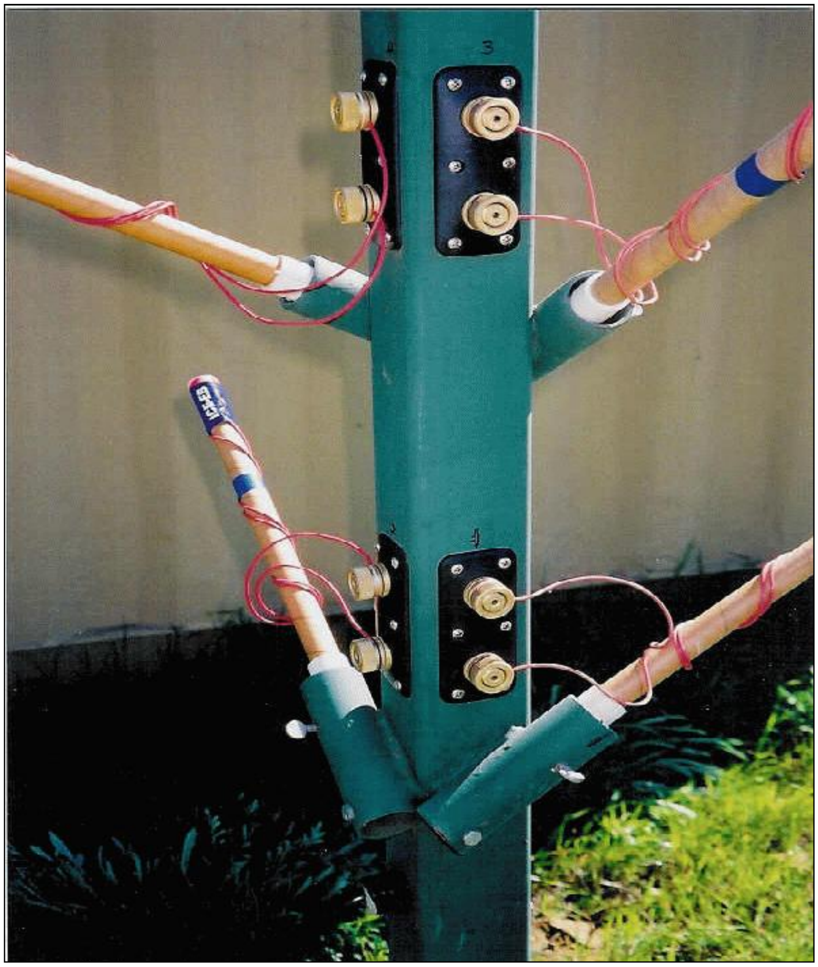

Figure 5.6   Close-up Photo of Flares

Figure 5.7 Flare Burning Inside Spark Arrestor

The basic concept of both the aircraft and ground seeding in the Santa Barbara II research program was to place as much seeding material as possible into the warmer updraft regions of the convective bands with cloud tops colder than freezing (i.e., -4° to -10° or -12°C). High output liquid fueled silver iodide generators were flown on the aircraft and 400 gram output ground silver iodide flares were fired every 15 minutes during the passage of convective bands over the single seeding site. The 400 gram flares (known as LW-83's) were considered very high output at the time, but have been replaced by even more effective (in terms of nuclei production) units utilized by NAWC starting with the 2001-2002 program.

The pyrotechnic flares used at the AHOGS sites although called 150 gram flares will emit around 15 grams of fast-acting silver iodide complex seeding material during a burn time of approximately four minutes. The 150 grams is the total weight of the flare. Ice Crystal Engineering (ICE) of Fargo, North Dakota manufactures these flares.

The output of the ICE flares has been tested at the Colorado State University (CSU) Cloud Simulation Laboratory. Table 5-2 provides the results of this testing. For reference purposes, 1 trillion is equal to 10^{12}. These flares exhibited activity up to temperatures of -4°C, which is considered very desirable since activity at these warm temperatures can result in the creation of more artificially generated ice crystals at lower altitudes in the clouds. A couple of advantages can result:

- Ground releases of seeding material can activate more quickly since the -4°C level will be reached sooner than -6 to -8°C which may have been the case with earlier generation flares.
- Conversion of water droplets to ice crystals at the -4°C level can release additional latent heat of fusion at lower altitudes within the seeded clouds, which should enhance the dynamic response of the clouds to seeding (refer to section 2.0 for a discussion).

A second important outcome of the testing of these flares at the Cloud Simulation Laboratory was that, when the seeding material was introduced into the cloud chamber, 63% of the ice crystal nucleation was produced within the first minute of introduction of the material into the chamber. It was therefore concluded that these flares were operating by the condensation-freezing mechanism (refer to Section 2). This is also considered to be an advantage over the earlier generation flares that no doubt operated by the contact nucleation process, which is much slower. This should mean that nearly all of the seeding material that reaches temperatures of -4°C within target clouds should quickly be utilized in producing ice crystals. Use of the earlier LW-83 flares, due to the slowness of the process, could mean that some of the seeding material was not activated in time to produce a seeding effect in the intended target areas. In fact, this characteristic may partially explain the extended downwind effects shown in Southwest Kern County during the conduct of Santa Barbara II, Phase I (see Figure 3.2).

Table 5-2 CSU Cloud Chamber Test Results for Ice Crystal Engineering Burn in Place Flare

Pyro type	Temp (bC)	LWC ($g\ m^{-3}$)	Raw Yield (g^{-1} Agl)	Corr. Yield (g^{-1} Agl)	Raw Yield (g^{-1} pyro)	Corr. Yield (g^{-1} pyro)	Yield (per pyro)
ICE	-3.8	1.5	$3.72x10^{11}$	$3.87x10^{11}$	$4.01x10^{10}$	$4.18x10^{10}$	$6.27x10^{12}$
	-4.0	1.5	$9.42x10^{11}$	$9.63x10^{11}$	$1.02x10^{11}$	$1.04x10^{11}$	$1.56x10^{13}$
	-4.2	1.5	$1.66x10^{12}$	$1.70x10^{12}$	$1.80x10^{11}$	$1.84x10^{11}$	$2.76x10^{13}$
	-4.3	1.5	$2.15x10^{12}$	$2.21x10^{12}$	$2.32x10^{11}$	$2.39x10^{11}$	$3.53x10^{13}$
	-6.1	1.5	$6.01x10^{13}$	$6.13x10^{13}$	$6.49x10^{12}$	$6.62x10^{12}$	$9.93x10^{14}$
	-6.3	1.5	$5.44x10^{13}$	$5.56x10^{13}$	$5.87x10^{12}$	$6.00x10^{12}$	$9.00x10^{14}$
	-6.4	1.5	$6.22x10^{13}$	$6.34x10^{13}$	$6.72x10^{12}$	$6.85x10^{12}$	$1.03x10^{15}$
	-10.5	1.5	$2.81x10^{14}$	$2.85x10^{14}$	$3.03x10^{13}$	$3.07x10^{13}$	$4.61x10^{15}$
	-10.5	1.5	$2.34x10^{14}$	$2.37x10^{14}$	$2.87x10^{13}$	$2.91x10^{13}$	$4.37x10^{15}$
	-4.2	0.5	$1.41x10^{12}$	$1.45x10^{12}$	$1.53x10^{11}$	$1.57x10^{11}$	$2.36x10^{13}$
	-6.0	0.5	$7.42x10^{13}$	$7.73x10^{13}$	$8.01x10^{12}$	$8.34x10^{12}$	$1.25x10^{15}$
	-10.5	0.5	$2.38x10^{14}$	$2.41x10^{14}$	$2.91x10^{13}$	$2.96x10^{13}$	$4.44x10^{15}$

The newer ICE flare can be compared to the earlier LW- 83 flare based upon tests conducted at the CSU Cloud Simulation Laboratory. Table 5-3 compares the ICE and LW- 83 output. Figure 5.8 provides a comparison of the nucleating characteristics of the ICE and the LW- 83 flares.

Table 5-3 Nuclei Production per Gram of Seeding Material for LW-83 and ICE Flares

Temperature (°C)	LW-83 (400g)	ICE (150g)
-4	2×10^{9}	1.5×10^{11}
-6	4×10^{10}	6×10^{12}
-10	3×10^{13}	3×10^{13}

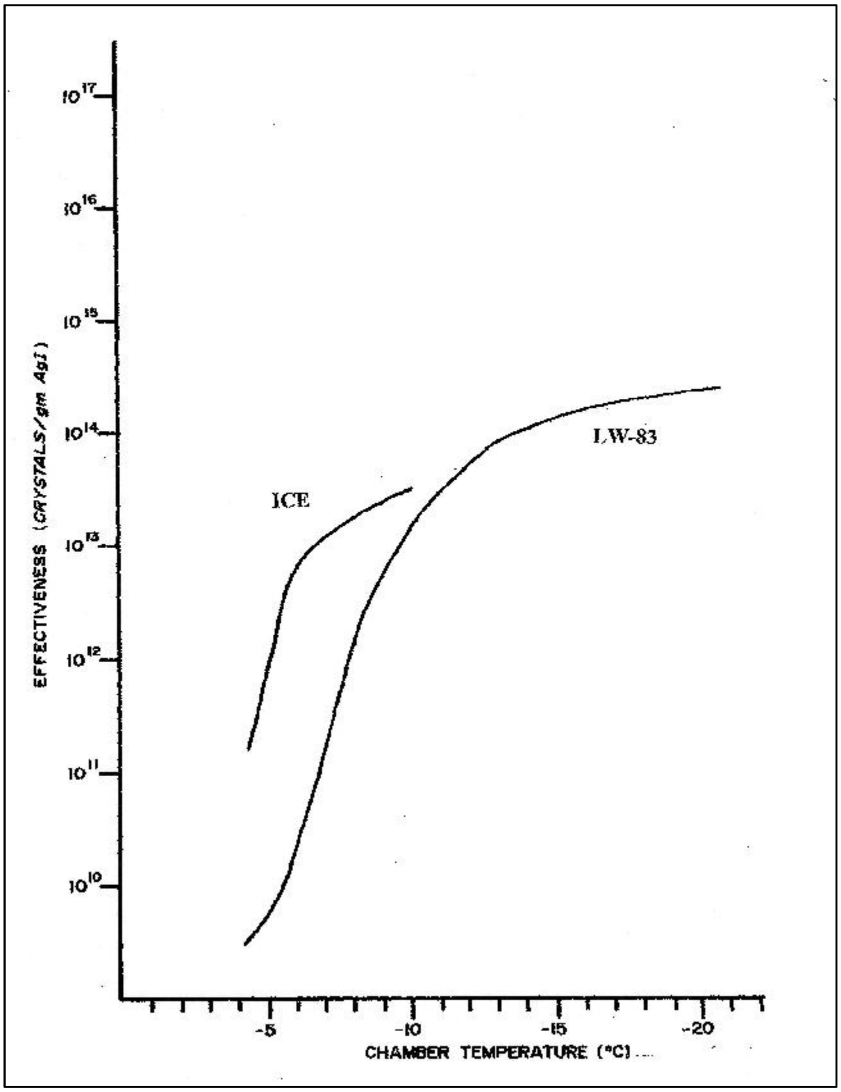

Figure 5.8 Comparison of Effectiveness of the LW-83 Verses the ICE Burn-in-place Flare, CSU Cloud Chamber Results

Figure 5.8 demonstrates that the ICE flare can produce more ice crystals (per gram of seeding material) in the critical temperature regions from -4 to -10°C (as much as two orders of magnitude higher at -4°C) than the older LW 83 flare, although the latter flare contained more seeding material. This temperature region is of prime importance to seeding-induced increases in precipitation in Santa Barbara County. Freezing supercooled water droplets in the upper (colder) portions of the bands may not necessarily contribute substantially to the production of increased rainfall at the ground. NAWC proposes that the ICE 150 gram burn in place flares be used at the ground flare sites established for the NRSAR program.

5.5 Cloud Seeding Aircraft

As mentioned earlier, a cloud seeding aircraft could be used to augment the basic ground based flare seeding program. Typical aircraft used on programs of this type include Cessna 340's, Cheyenne II's and King Air 90's. Any seeding aircraft used should be certified for flight in known icing conditions due to the type of clouds that would be seeded.

This aircraft would be equipped with two burn in place flare racks (mounted on the trailing edge of each wing). The same 150-gram ICE flares used at the ground sites would be used in the burn in place flare racks.

5.6 Seeding Operations

NAWC's conceptual model of the dynamics of the convective bands is that they have a similar structure to summer squall lines in the Great Plains. NAWC believes that the primary low to mid-level inflow to these bands is along the leading edge of the bands. The inflow regions are thought to be the likely accumulation zones of supercooled liquid cloud droplets water, which are the targets of the seeding. Consequently, this is the desired region for the introduction of the seeding material. This would mean that flares burned at the ground sites should be timed to occur as the leading edge of the bands, as determined by weather radar imagery (available at approximately 5 to 6 minute intervals) from the San Francisco, San Joaquin or Vandenberg AFB NEXRAD radars, approach the ground sites. The seeding aircraft would be flown along the leading edge of the bands somewhere between the freezing and -5°C level. Low-level winds need to be considered in terms of targeting of seeding effects as well as the avoidance of seeding over suspension areas. The HYSPLIT model, discussed in Section 5.8.2 would be used in real time to help predict the plume dispersion from flares burned. In addition to the specific criteria in the above, which focus on the presence of convective bands, NAWC also recommends consideration of some generalized seeding criteria as provided in Table 5-4. These are general guidelines and the Project Meteorologist may override these criteria based upon his or her professional judgement about the meteorological conditions associated with a specific storm.

Table 5-4 Generalized Seeding Criteria

1) CLOUD BASES ARE BELOW THE MOUNTAIN BARRIER CREST.
2) LOW-LEVEL WIND DIRECTIONS AND SPEEDS WOULD FAVOR THE MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THEIR RELEASE POINTS INTO THE INTENDED TARGET AREA. WINDS AT THE 850 MB LEVEL (~5,000 FT MSL) ≤ 50 KTS.
3) NO LOW LEVEL ATMOSPHERIC INVERSIONS OR STABLE LAYERS THAT WOULD RESTRICT THE VERTICAL MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THE SURFACE TO AT LEAST THE -5°C (23°F) LEVEL OR COLDER.
4) TEMPERATURE AT MOUNTAIN BARRIER CREST HEIGHT EXPECTED TO BE -5°C (23°F) OR COLDER.
5) TEMPERATURE AT THE 700 MB LEVEL (APPROXIMATELY 10,000 FEET) EXPECTED TO BE WARMER THAN -15°C (5°F).
6) CLOUD TOP TEMPERATURES < -25°C (-13°F)

A detailed operations plan should be developed by the contractor specifically for this program. This plan would be available as a reference for all program personnel. An important part of this Operations Plan will be program suspension criteria; criteria that specifies under what conditions seeding operations should be suspended or not initiated. Table 5-5 provides some recommended criteria. Most of these criteria were taken from criteria currently being used on the Twitchell and Upper Santa Ynez watershed programs. Some additional criteria may need to be considered based upon predicted or observed streamflow on certain sensitive watersheds.

Another possible concern could be rainfall intensities. Criteria could be developed for some cutoff criteria (e.g. > 1.00" per hour).

Table 5-5 Recommended San Antonio and Nacimiento Watersheds Suspension Criteria

1. Whenever the National Weather Service (NWS) issues a severe storm, precipitation, flood warning or flash flood warning that affects any part of the project area, the project meteorologist shall suspend operations, which may affect that part. Operations will be suspended at least for the period that the warning is in effect.

2. The Project Meteorologist or MCWRA personnel shall retain independent authority to suspend cloud seeding operations for any part, or all of the project area in the event that unforeseen conditions develop during storm events which in their best judgment have the potential to cause flooding or other adverse conditions anywhere within the project area.

3. If either of the target reservoirs fills during the winter season, operations would be suspended unless the storage drops below the capacity of the reservoir later during the winter season.

5.7 Weather Data

There is a wealth of weather information available via the internet. There are several products that are useful in the conduct of cloud seeding operations. NAWC's web site (www.nawcinc.com) contains an extensive list of useful weather links.

The following list some of the weather products that may be useful in the conduct of the Monterey County program:

1) The Monterey and San Luis Obispo ALERT weather networks.

2) The National Weather Service surface, upper air and precipitation observations and predictions (e.g., the GFS, NAM and WRF models). Other forecast models are discussed in the next section.
3) The California River Forecast Center Quantitative Precipitation Forecasts (QPFs).
4) Satellite images; infrared (IR), water vapor (WV), or visible. IR images provide information both day and night and provide information on cloud top temperatures. Visible images are only available during daylight hours but the resolution on the images is better than the resolution on the IR products.
5) National Weather Service NEXRAD radar images, showing reflectivity values associated with precipitation near the times when seeding occurred, available at approximately 5 to 6 minute intervals. The typical displays are called Plan Position Indicator (PPI) images, which are horizontal depictions of the radar reflectivity values within range of the radar. These images give an indication of the type, intensity, and extent of precipitation during seeding periods. The NEXRAD radars through the Doppler feature also observe wind direction and velocity, which is part of the NEXRAD design. Plots of winds in the vertical in 1000-foot increments are available in the radar data, known as Velocity Azimuth Displays (VAD). Customized displays utilizing NWS NEXRAD data will also be used (for example, those available on WeatherTap).
6) Skew-T upper-air soundings from Vandenberg AFB. The Skew-T sounding is a plot of temperature, dew point, and winds vs. height, observed by a radiosonde (balloon borne weather instrument). This sounding information is useful for analyzing various parameters of the atmosphere including temperature and moisture profiles, and convective potential. Soundings are available twice daily at 0400 and 1600 PST. The 700 mb (approximately 10,000 feet) temperatures are frequently reported in the storm summaries. NAWC typically prefers to see these temperatures at -5°C or colder during seeded periods since silver iodide becomes effective as a seeding agent between -4° and -5°C. With ground-based seeding, the lower the height of the -5°C level, the quicker a seeding effect will begin to be produced as the convective elements embedded in the convective bands begin to move over Monterey and San

Luis Obispo counties. These convective elements vertically transport the seeding material from the ground seeding sites to colder temperatures aloft.

7) National Weather Service weather watches, weather warnings, and flash flood warnings.

5.8 Computer Modeling

Specialized computer models can be used in the conduct of this program. These models are of two basic types: 1) those that forecast a variety of weather parameters useful in the conduct of the cloud seeding program (e.g. NAM or WRF) and 2) those that predict the transport and diffusion of seeding materials (e.g., Hybrid Single-Particle Lagrangian Integrated Trajectory, known as HYSPLIT).

The National Oceanic and Atmospheric Administration (NOAA) runs standard atmospheric models including the North American Model (NAM) and the Global Forecast System (GFS) model in forecasting seedable events and associated parameters of interest (e.g. temperatures, winds, precipitation). These models can be used, especially for longer range forecasts. A more sophisticated model can be used for shorter range forecasts. This is the Weather Research and Forecasting (WRF) model developed by the National Center for Atmospheric Research (NCAR) and NOAA. This model has shown considerable skill in predicting precipitation, pressure fields, wind fields and a variety of other parameters of interest in conducting the cloud seeding operations. Several web sites provide WRF model output (e.g., NOAA, NCAR, and University of Utah).

The HYSPLIT model developed by NOAA provides forecasts of the transport and diffusion of either ground or aerial releases of some material, which in our case would be silver iodide seeding particles. The WRF and HYSPLIT models will be discussed separately in the following.

5.8.1 WRF Model

The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. It features multiple dynamical cores, a 3-dimensional variational (3DVAR) data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers.

The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), the National Centers for Environmental Prediction (NCEP), the Forecast Systems Laboratory (FSL), the Air Force Weather (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. WRF provides operational forecasting a model that is flexible and efficient computationally, while offering the advances in physics, numeric, and data assimilation contributed by the research community.

The WRF model has a 3km grid spacing compared to the more standard grid model spacing of 12 km (e.g. NAM model), plus it is re-initialized every hour using the latest radar observations. Smaller grid spacing in models generally produce more accurate predictions especially in complex terrain (e.g. mountainous areas). The NAM and GFS models are currently re-initialized every 6 hours. Hourly forecast outputs from the High Resolution Rapid Refresh (HRRR) model are available for a variety of parameters out to 15 hours. Table 5-6 provides a summary of some of forecast parameters of interest in conducting cloud seeding program.

Since the design of the program which is focused upon seeding convective bands, and the seeding techniques as described in Section 5.6, it can be seen that forecasts of convective band locations are not a requirement but are useful when using the ground-based seeding sites. Seeding decisions for ground-based sites can be made using real-time NEXRAD radar information indicating when a convective band is approaching a particular seeding site. These forecasts become more useful in airborne operations in order to provide lead time in filing flight plans to coincide with convective band passages. The precipitation type forecasts are useful when considering suspension criteria.

Table 5-6 HRRR Forecast Parameters of Interest

Parameter	Application
1km above ground level reflectivity	Forecast of convective band locations based on radar returns 1km above ground
Composite reflectivity	Forecast of convective band locations using reflectivity values from different scan elevations. This is useful when bands approach the radar site since low elevation scans may go underneath the bands.
Max 1km above ground level reflectivity	Forecasts that pinpoint the location of the heart of the convective bands
1 hour accumulated precipitation	Forecasts of radar derived estimates of precipitation reaching the ground in a one-hour period (QPF).
Total accumulated precipitation	Forecasts of radar derived estimates of precipitation reaching the ground for a specified time period, for example 1-6 hours in the future (QPF).
850 mb winds	Forecasts of the 850-mb (~4,000 feet) wind direction are useful in determining if and when wind directions may go out of bounds in regards to suspension criteria.(e.g., avoiding burn areas)
700 mb temperature	NAWC uses this level, which is ~10,000 feet, to indicate whether silver iodide will activate. Temperatures < -5°C are desirable at this level
700 mb vertical velocity	Forecasts the strength of the upward or downward movement at ~the 10,000 foot level. Stronger updrafts favor transport of seeding material to colder, more effective cloud regions.
Echo top height	Forecasts of cloud echo tops. Can be useful in determining whether the cloud tops are forecast to be cold enough for silver iodide to be effective (~-5°C) and perhaps too cold <-25°C to produce positive seeding effects.

5.8.2 HYSPLIT Model

The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model is the newest version of a complete system for computing dispersion simulations. The model can be run interactively online or downloaded to run on a user's local computer. NAWC has utilized the HYSPLIT model to predict the transport and diffusion of silver iodide seeding material during selected storm periods in Santa Barbara County during the past six winter seasons of operations.

The depictions from HYSPLIT are only of the transport and dispersion of the seeding plumes. The model does not include microphysical process such as nucleation of the seeding material or the location of expected seeding impacts. Of note is the fact that the National Center for Atmospheric Research (NCAR) has been developing and validating a plume transport, seeded microphysical interactions and fallout of seeding generated particles model. This model may be available to the public sometime in the future.

5.9 HYSPLIT Modeling for the Monterey County Seeding Program

The HYSPLIT model was run to assess the potential use of six ground-based generator sites. Although more or less sites may become realized for any potential program affecting the watersheds in the county, six locations were used for the purposes of the plume modeling. The six potential ground sites were selected from Google Earth with the intent being to locate sites along ridgelines or elevated locations upwind of the proposed target area. Figure 4.2 from section 4.0 indicates that the 700-mb wind directions with convective bands range from 180° to 280° with prevailing directions from 220° – 260°. Wind directions in meteorology indicate the direction the winds are blowing from. For example, a 270° wind direction would mean the winds are blowing directly from the west towards the east. The 700-mb level (approximately 10,000 feet MSL) is a good representation of the movement of convective bands as well as the mean transport of ground-based seeding plumes. Given these considerations, ground-based generator sites should be located upwind of the proposed target in the 180° to 270° quadrant.

HYSPLIT modeling was performed on four convective bands that moved through the county during water years 2010-2014. The HYSPLIT output for these cases is shown in Appendix A. The time of band passage through the proposed target area was estimated from the time of convective band passage through San Luis Obispo/Monterey County and the 700-mb wind speeds. Several representative cases were chosen from this five-year period, with varying temperature and wind speed values. Table 5-7 below shows these periods with other information relevant to band passage through the intended target area.

Table 5-7 Storm Periods Used for HYSPLIT Model Runs

Date	Passage Time (Z)	700 mb temperature (°C)	Wind Speed (knots)	700 mb wind direction (degrees)	Synoptic feature
12/05/2010	0200-0600	-2	30-40	180-200	Trough/Upper low
04/13/2012	0500-0700	-8	35-45	230-260	Open Trough
04/01/2014	1900-2200	-9	25-35	260-280	Deep trough
12/12/2014	0200-0600	-4	40-50	220-240	Upper trough

The map in Figure 5.9 illustrates the theoretical target area, outlined in white and six possible ground sites. Each of the ground sites is numbered and corresponds to the latitude, longitude, and elevation listed in Table 5.8.

Table 5-8 Coordinates and Elevations for Potential Ground Sites

Site	Latitude	Longitude	Elevation (feet)
1	35.695° N	121.099° W	2930
2	35.698° N	121. 187° W	3160
3	35.741° N	121.253° W	2350
4	35.816° N	121.148° W	2250
5	35.868° N	121.349° W	3000
6	35.971° N	121.443° W	3110

HYSPLIT was used to simulate ground seeding. Locations in Table 5.8 were chosen based on sites that would accommodate a number of wind directions favoring the transport of the seeding material into the target area. As is the case with many of the storm systems that move across central California during the winter months, the prevailing wind direction when convective band passages occur was generally that of a southerly or westerly component.

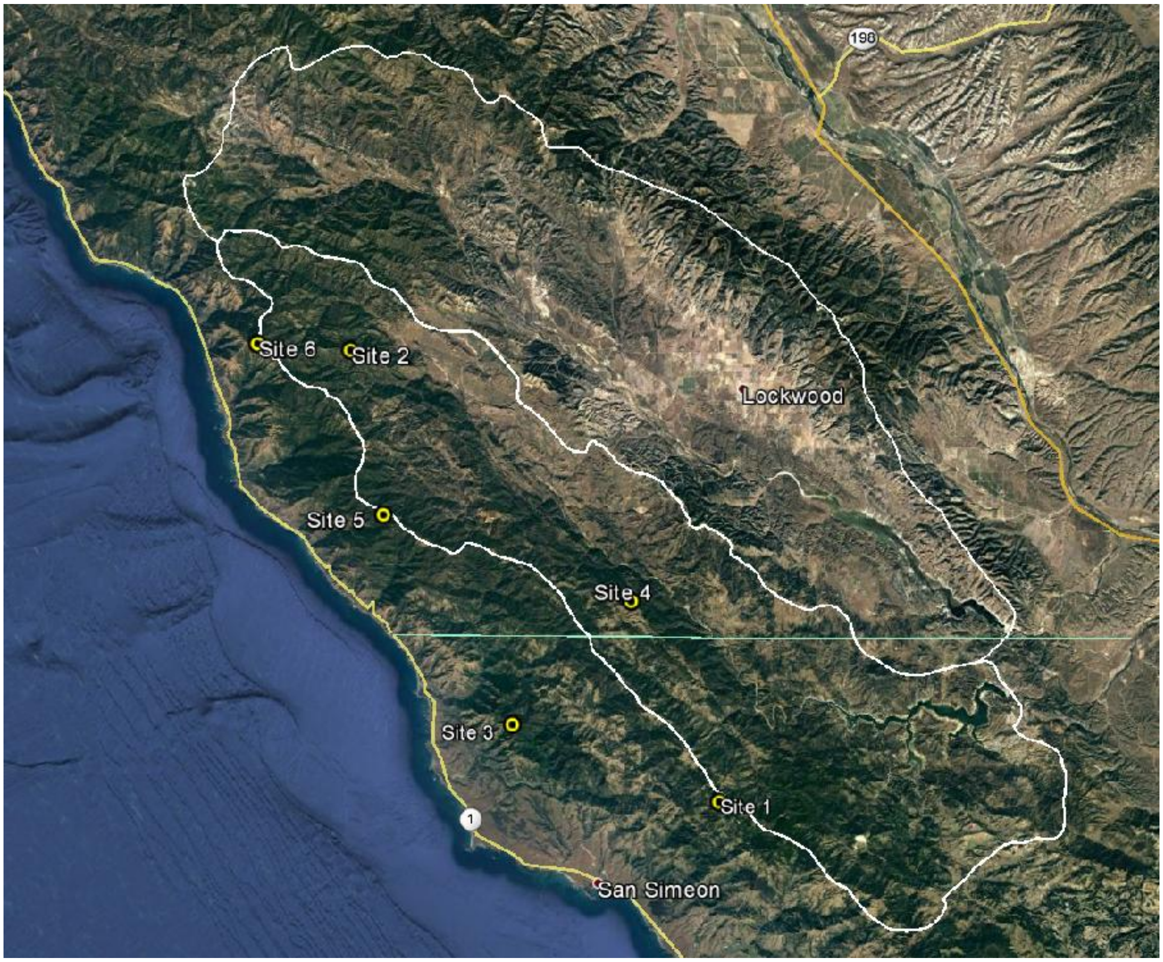

Figure 5.9 Target Area Base Map and Potential AHOGS Locations

Figure 5.10 shows a HYSPLIT plume generated by the six potential ground-based sites when a convective band was moving into the proposed target area. Each of the sites emits a plume that is modeling the seeding material and its transport over the target areas. The color of the plumes, ranging from yellow to blue to green represents the relative concentration of seeding material. This example is of a forecast of two hours of transport. The remainder of the cases were one-hour forecasts. Plumes in the HYSPLIT model would continue to extend further with longer run times due to the lack of a nucleation and precipitation mechanism to remove the seeding material in the HYSPLIT simulations. The other HYSPLIT simulations that were done for this study are located in Appendix A. If four sites were installed and the site logistics were favorable, sites 1, 3, 5, and 6 are recommended. Reasons for these choices can found be found in Section 7.0.

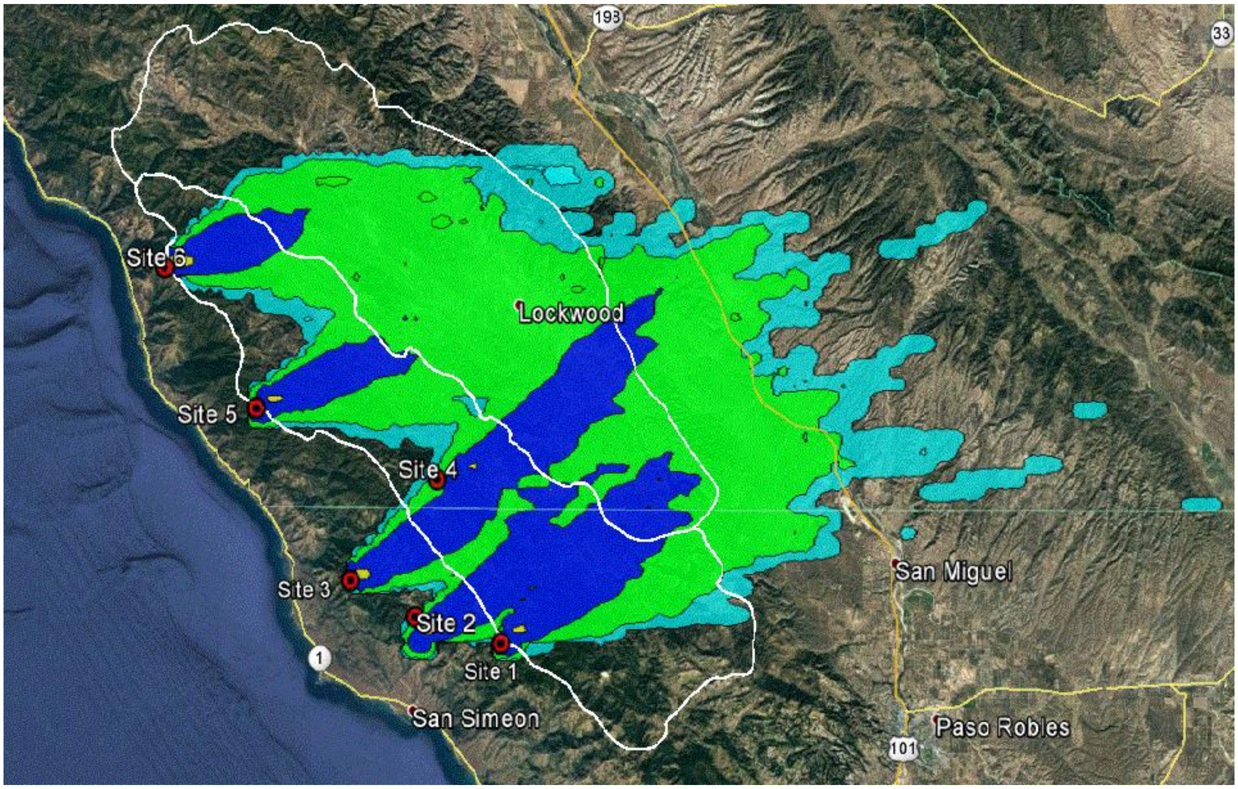

Figure 5.10 Two-hour HYSPLIT simulation for April 1, 2014 during the Initial Passage of a Convective Band Associated with an Upper Low along the Coast (yellow and dark blue near the center of the plumes represent the highest concentrations of material in the simulation, while the green and light blue represent lower concentrations around the edges of the plumes).

Aircraft seeding can also be modeled using the HYSPLIT program. The image in Figure 5.11 shows a potential aircraft flight denoted by the white line and red aircraft icon. The plumes each represent where a flare was fired. Since the flares burn for four minutes and only a discrete location was used in this simulation, the plumes would be wider than those shown in this figure. This case only shows four flares being fired, but additional flares can be fired if needed to sufficiently seed both target areas. This case was also modeled with ground generators which can be seen in Appendix A. In this case, winds were rather strong and the coast limits how far west cloud seeding generators can be placed. A seeding aircraft is useful in these situations, where it can fly offshore and can effectively seed both target areas, regardless of how strong the winds are. Aircraft would also allow better targeting of the Nacimiento River Drainage as strong winds with some storm events may not allow for activation of ground-released seeding material quickly enough to have effects there.

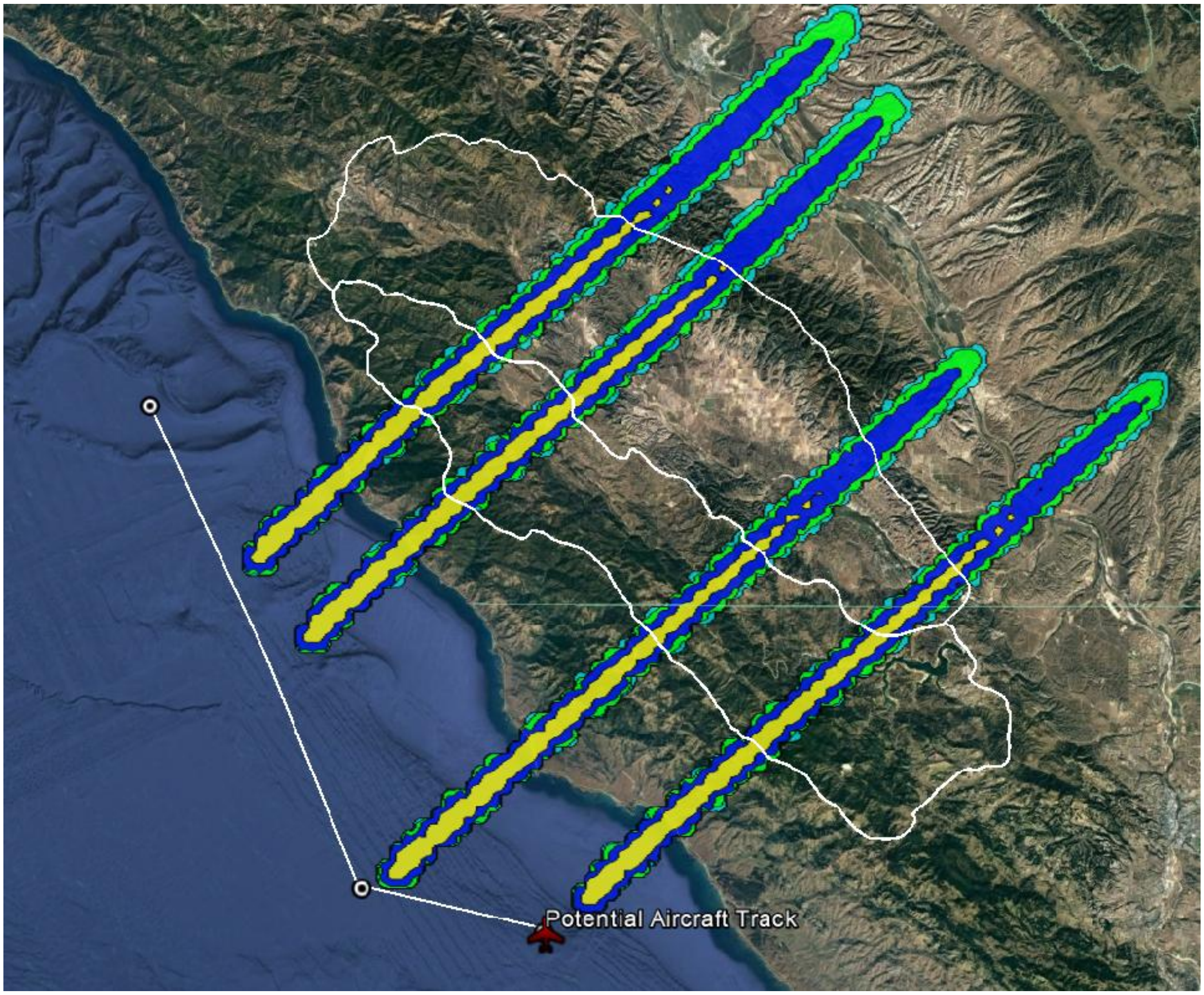

Figure 5.11 Two-hour HYSPLIT simulation for April 13, 2012 via Aircraft Seeding

6.0 PRECIPITATION AND STREAMFLOW INCREASE ESTIMATES

The seasonal seeding precipitation increase estimates were determined to be between approximately 9% and 17% (Griffith, et al, 2015) for the long-term Santa Barbara operational program. NAWC believes these increases would be representative of coastal Monterey and northern San Luis Obispo Counties as well since NAWC's program design calls for the seeding of convection bands, which is the same seeding design as that being used on the Santa Barbara program. Regression equations were developed relating stream gauge data versus seasonal (November – April) precipitation for available sites in the area. Streamflow data for the Nacimiento River below Sapaque and San Antonio River near Lockwood were obtained from Monterey County personnel, as well as available precipitation records for the Nacimiento Dam and San Antonio Dam. Nacimiento River streamflow for the 1972-2016 water years and San Antonio River streamflow data for the 1967-2016 water years, were utilized in this analysis. The average **annual** streamflow values based on the available data periods were 121,286 acre-feet (Nacimiento Dam) and 72,155 acre-feet (San Antonio Dam). Average seasonal (November – April) precipitation for the period was 13.59" at Nacimiento Dam and 13.34" at San Antonio Dam.

Correlations between annual streamflow and November – April seasonal precipitation totals at a number of precipitation gauges in the region were tested, including the precipitation data from the Nacimiento Dam and San Antonio Dam sites. Seven precipitation gauge sites (Nacimiento Dam, San Antonio Dam, Atascadero, King City, Mehlschau #38, San Luis Obispo Polytech, and Monterey) were selected, as having the best overall correlation to the streamflow data at the two reservoirs. Data from the five other precipitation sites were obtained from the Desert Research Institute Website (http://www.wrcc.dri.edu/Climsum.html) which links to archived NOAA cooperative data. These precipitation gage sites also had data available back to 1967 or earlier, spanning the period of streamflow data used in the analysis. Appendix B contains the raw data sets used in the development of the precipitation/streamflow regressions. Using an average of several precipitation gauges provides (in this case) a more accurate overall approximation of the watershed precipitation (and thus, runoff) than simply using the precipitation data from dam sites, as evidenced by higher correlations obtained in the regression equations utilized in this analysis. Either approach is valid, however, as one could utilize only rainfall data from within the watershed to the extent that such data are available. Estimates were made for a few missing monthly precipitation totals at some precipitation sites, based on corresponding data from nearby sites and comparison of the long-term monthly averages. These individual month estimates provide a more complete data set and have a minimal effect on the regression equations.

Table 6-1 shows the latitude/longitude of the streamflow and precipitation data sites used in the regression equations, as shown on the map in Figure 6.1. Figure 6.2 is a close-up of the drainages and the two streamflow gauge locations, as well as the Nacimiento and San Antonio Dam locations.

Table 6-1 Locations of Precipitation and Streamflow Gauge Data

Precipitation Site	**Latitude**	**Longitude**
Nacimiento Dam	35° 45’	-120° 53’
San Antonio Dam	35° 48’	-120° 53’
San Luis Obispo Polytech	35° 18’	-120° 40’
Atascadero Mutual Water	35° 29’	-120° 38’
Mehlschau #38	35° 04’	-120° 30’
King City	36° 12’	-121° 08’
Monterey	36° 36’	-121° 54’
Streamflow Site	**Latitude**	**Longitude**
Nacimiento below Sapaque R (USGS 11148900)	35° 47’	-121° 06’
San Antonio River near Lockwood (USGS 11149900)	35° 54’	-121° 05’

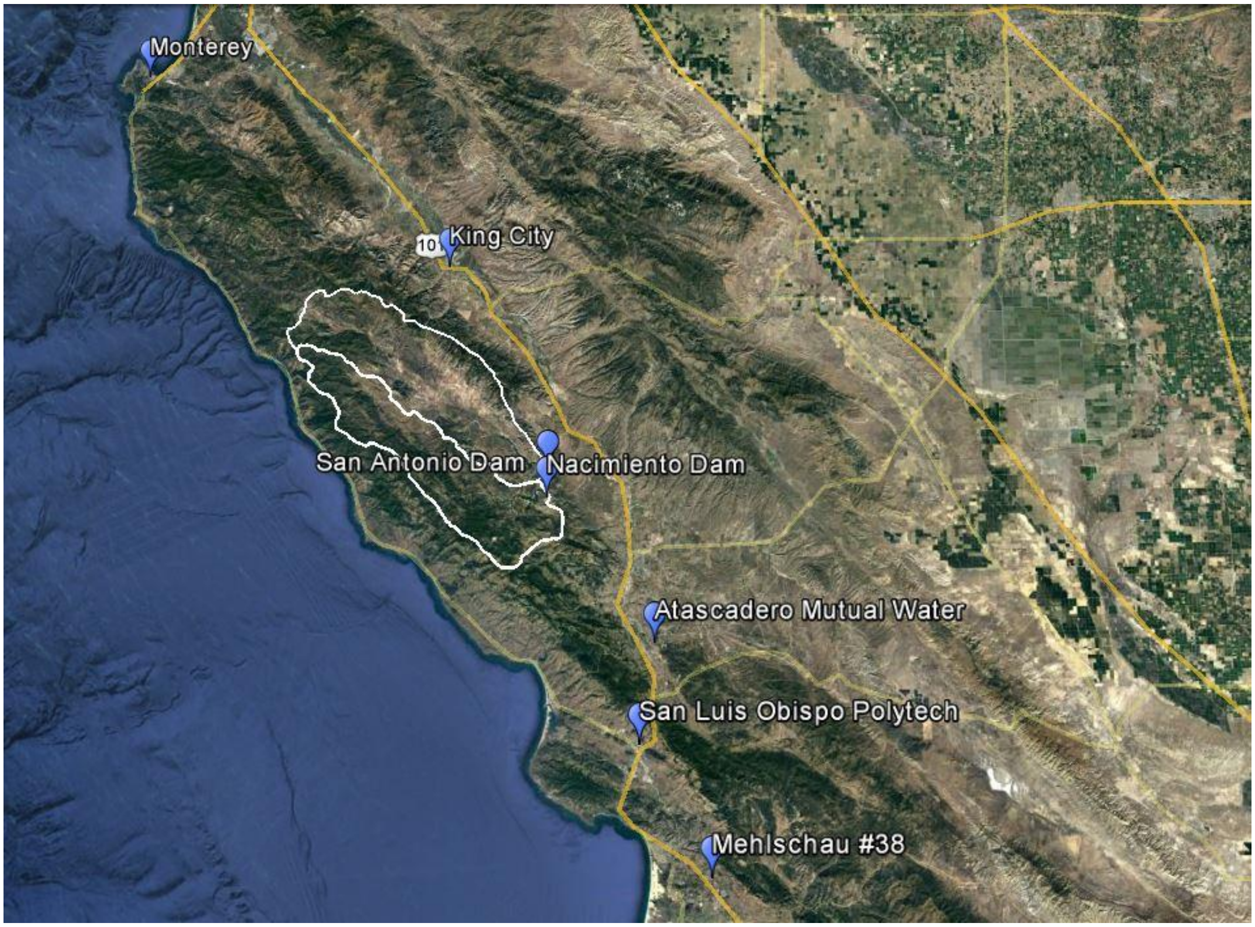

Figure 6.1 Precipitation gauges (blue markers) used in the development of regression equations with the streamflow data; watersheds outlined in white

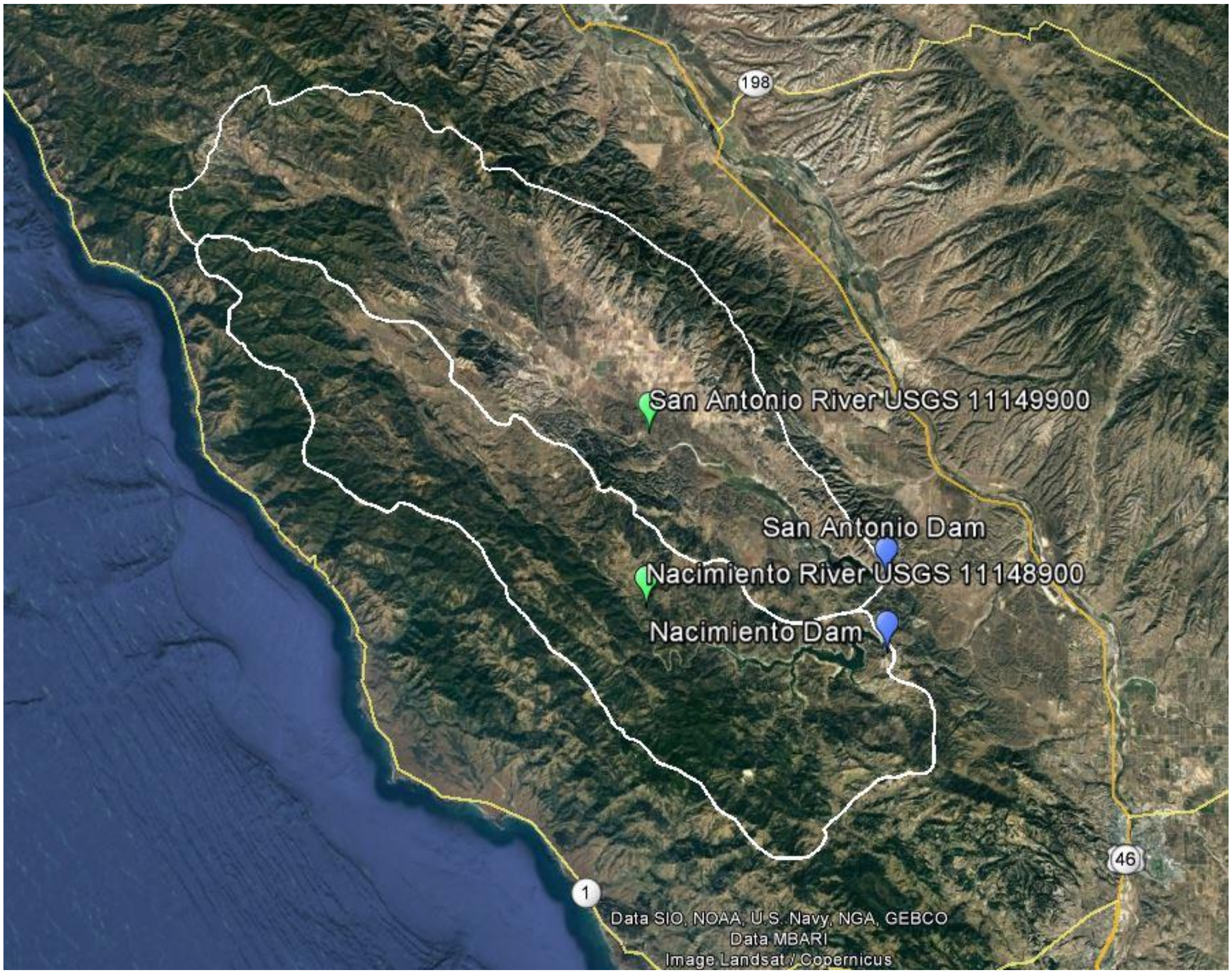

Figure 6.2 Close-up of the watersheds (white), streamflow gauges (green), and the San Antonio Dam and Nacimiento Dam locations (blue) as shown in Figure 6.1

The regression equations provide estimates of streamflow increases based on a given precipitation increase. Based upon previous experience obtained in numerous other studies, streamflow increases will typically be greater percentage-wise than the corresponding seasonal precipitation increase from seeding because a certain amount of rainfall is needed to recharge soil moisture before runoff begins. This is related to the negative offset term in the regression equations. Therefore, applying a given increase to the total seasonal precipitation will generate a greater percentage increase in runoff since (under normal circumstances) all of the additional precipitation is contributing to additional streamflow, after the soil recharge requirements have been met. This may not always be the case, such as in water years with much lower than normal precipitation that could lead to minimal or no runoff. The two regression equations developed based on Nacimiento River and San Antonio River streamflow data yielded similar results. The regression equations are provided below and the resulting estimated annual streamflow increases in an **average water year**. Table 6-2 provides estimated streamflow increases based on estimated seasonal precipitation increases of 9% or 17% due to seeding. For a 9% increase in seasonal precipitation, the estimated increases in streamflow are 20,590 AF for the Nacimiento River and 13,368 AF for the San Antonio River, for a total increase of 33,958 AF in an average season. For a 17% increase in precipitation, the estimated increases in streamflow are 38,891 AF for the Nacimiento River and 25,250 AF for the San Antonio River, for a total increase of 64,141 AF in an average season. The two regression equations used in this analysis are provided below:

- **Equation 1 Regression equation for Nacimiento River streamflow:**

  $Y = 15{,}005(X) - 107{,}487$

  where Y is annual total streamflow in acre-feet, and X is the average of the precipitation gauge seasonal (November – April) totals in inches from the sites shown in Table 6-1. The offset term in the equation (-107,487) is in acre-feet. The r-value for equation 1 is 0.956.

  The average value of X for the historical period (1972-2016 for this equation) is 15.25 inches. This is the value one would apply the seeding increase (e.g. 9% or 17%) to when using this particular equation, even though some of these precipitation sites are not actually in the target area.

- **Equation 2 Regression equation for San Antonio River:**

  $Y = 9584(X) - 76{,}377$

  where Y is the annual total streamflow in acre-feet, and X is the average of the precipitation gauge seasonal (November – April) totals in inches from the sites shown in Table 6-1. The offset term in the equation (-76,377) is in acre-feet. The r-value for equation 2 is 0.929.

  The average value of X for the historical period (1967-2016 for this equation) is 15.50 inches. This is the value one would apply the seeding increase (e.g. 9% or

17%) to when using this particular equation, even though some of these precipitation sites are not actually in the target area.

Table 6-2 Estimated Streamflow Increases for 9% and 17% Seasonal (November - April) Precipitation Increases

Stream gauge site	Regression for Nacimiento River (Eq.1)	Regression for San Antonio River (Eq.2)	Total Estimated Increase
9% Precipitation increase	+17.0% (20,590 AF)	+18.5% (13,368 AF)	33,958 AF
17% Precipitation increase	+32.1% (38,891 AF)	+35.0% (25,250 AF)	64,141 AF

The information provided in Table 6-2 will be used in the next section to estimate the potential benefit/cost ratios from the operation of a seeding program.

If a seeding program is conducted for these watersheds, the data utilized in this section could be utilized to provide post-hoc estimates of precipitation/streamflow increases due to seeding during the seeded seasons. This could be accomplished by target/control regressions, potentially using the five precipitation sites outside the target area as controls and the two reservoir precipitation gauge sites as target sites. However, it may be better to utilize the streamflow data as the target data (with the same precipitation gauges that are outside the target area used as control sites), since the streamflow should be more representative of the target area as a whole than are the two precipitation gauge sites at the reservoirs.

7.0 ESTIMATED PROGRAM COSTS AND BENEFIT/COST ESTIMATES

There could be some upfront costs in establishing a winter cloud seeding program for the NRSAR. It is likely that some form of environmental documentation would need to be conducted. The other initial expense, should the ground-based seeding mode be implemented, would be conducting site surveys and obtaining leases for three or four AHOGS ground seeding sites. A rough estimate of the cost of completing this task is $15,000. The estimated costs to fabricate and install three or four AHOGS units are as follows:

Three AHOGS Units

Fabrication and Testing- 3 units @ $30,000	$90,000
Installation	16,000
Estimated Total	$106,000

Four AHOGS Units

Fabrication and Testing- 4 units @ $30,000	$120,000
Installation	20,000
Estimated Total	$140,000

After the initial fabrication and installation there would be annual operating and reporting expenses. There would be both fixed and reimbursable costs. The Monterey County Water Resources Agency would only be charged for the actual usage of the reimbursable elements in this budget. Contractors typically estimate reimbursable costs on the high side to avoid running out of budgeted funds. Therefore, the estimated total costs are frequently not reached in a given seeded season. Here are the estimated costs for a five month program using four AHOGS units. These costs assume the initial investment of $140,000 has been made.

Five Month Program with Four AHOGS Sites

1. Set-up, Take-down and Reporting		$25,000
2. Five months Fixed Cost @ $13,000		65,000
	Sub-Total	$90,000
3. Estimated Reimbursable Costs		
200 ground flares @ $90/flare		18,000
	Estimated Total	$108,000

An airborne only seeding program might be considered which would avoid the upfront costs of the AHOGS units. The following provide estimates of the cost of a five month aircraft only seeding program.

Five Month Aircraft only Program

1. Set-up, Take-down and Reporting		$53,000
2. Airborne Operations, Five Months Fixed Cost @ $30,000		150,000
	Sub-Total	$203,000
3. Estimated Reimbursable Costs		
80 flight hours @ $550/hr.		$44,000
60 hours airborne seeding, 4 flares/hr. @ $90/flare		21,600
	Sub-Total	$65,600
	Estimated Total	$268,600

The estimated costs for a five month program using four AHOGS sites and three months of aircraft seeding (this has been the typical project design followed on the Santa Barbara County Water Agency program) are as follows. These costs assume the initial investment of $140,000 has been made.

Five Month Program with Four Ground Flare Sites and Three Months with Seeding Aircraft

1. Set-up, Take-down and Reporting		$66,000
2. Ground Operations, Two months Fixed Cost @ $13,000		26,000
3. Ground and Airborne Operations, Three Months Fixed Cost @ $44,000		132,000
	Sub-Total	$224,000
4. Estimated Reimbursable Costs		
50 flight hours @ $550/hr.		$27,500
40 hours airborne seeding, 4 flares/hr. @ $90/flare		15,200
200 ground flares @ $90/flare		18,000
	Sub-Total	$60,700
	Estimated Total	$284,700

Table 6-2 taken from section 6 is duplicated here as Table 7-1.

Table 7-1

Estimated Streamflow Increases for 9% and 17% Seasonal (Nov-Apr) Precipitation Increases

Stream gage site	Regression for Nacimiento River (Eq.1)	Regression for San Antonio River (Eq.2)	Total Estimated Increase
9% Precipitation increase	+17.0% (20,590 AF)	+18.5% (13,368 AF)	33,958 AF
17% Precipitation increase	+32.1% (38,891 AF)	+35.0% (25,250 AF)	64,141 AF

An important consideration in achieving the estimated increases in Table 7-1 by seeding mode is the potential locations of AHOGS units that could be used to target the Nacimiento drainage. A complication arises due to the proximity of this drainage to the Pacific Ocean coastline. This feature limits the distance upwind of this drainage in which AHOGS sites may be installed. This is important in terms of the targeting of seeding effects since seeding materials released from ground sources need to rise to temperatures of -5^0 C in the convections bands before the silver iodide seeding material becomes an active seeding agent. Once ice crystals are formed, time is required for them to grow into snowflakes that can begin their descent, turn into raindrops and reach the ground. Each of the above steps takes time all of which are occurring in storm features that are being advected downwind by the storms low-to mid-level environmental wind field. The stronger the wind field and the warmer the airmass, the further downwind the seeding effects will occur. In general, AHOGS units installed in or upwind of the Nacimiento drainage will likely have more impact in the San Antonio drainage. Some impacts, however, are expected in the Nacimiento drainage in the colder, lighter wind cases. **NAWC arbitrarily assumes that one-half of the predicted streamflow for the Nacimiento drainage in Table 7-1 could be produced through the ground based AHOGS seeding.** Aircraft seeding has no such limitations since seeding of convection bands can be accomplished off the coast of Monterey County if needed to target this drainage. NAWC employs this approach on the Santa Barbara County cloud seeding program.

It would be useful to have a computer model that could predict the potential targeting of seeding effects on this program for Monterey County. Regarding the state of using models to predict the transport, growth and fallout of augmented precipitation; the National Center for Atmospheric Research (NCAR) has been developing and validating a plume transport, seeded microphysical interactions and fallout of seeding generated particles model for the Idaho Power Company. This model may be available to the public in the future. It would be very useful to have a model of this type to run in near real-time to help make the appropriate seeding decisions. It is our understanding that the current version requires a supercomputer and is very expensive to run. Even if such a model were available its usefulness on the Monterey County program might be limited. The reason for this is contained in Section 2.0 that explains there may be both static and dynamic effects of seeding. It was theorized in the analysis of the Santa Barbara II, Phases I and II research programs that some (perhaps a significant majority) of the seeding effect was due to dynamic responses within the seeded convection bands. A very sophisticated model, which has been verified, would be needed to correctly predict the occurrence and location of such a dynamic response from seeding convection bands.

NAWC asked the MCWRA for estimates of the value of additional inflow to the target drainages. The MCWRA was unable to provide any estimates. The question is what is the value of water in the two target reservoirs for the primary use, which appears to be irrigated agriculture. Lacking any specific estimates, we decided to use a range of possible values. The arbitrary values were $50, $100, $200 and $500 per acre-foot. By combining this information with the data provided in Table 7-1 and the estimated costs, calculations can be made of the potential cost of the additional inflow per acre-foot as well as estimates of benefit/cost ratios. Some assumptions need to be made in this analysis:

- The estimates of increases in precipitation and the resultant estimates of increases in the annual average inflow to the reservoirs are relatively accurate.
- When considering a ground-based seeding program, the estimated increases in precipitation and inflow would likely be lower. NAWC has no data that would enable us to estimate this reduction. The analysis of the Santa Barbara program (Griffith, et al, 2015) was typically for a five month program with ground seeding and three months of airborne seeding. One rather crude approach can be used by assuming the 9% estimated increases in precipitation and the resultant increases in inflow could be achieved with four AHOGS ground sites operating for five months and in a similar fashion the 17% increases in precipitation and resultant inflow could be achieved with four AHOGS grounds sites operating for five months and a seeding aircraft operating for three months. Effects from aircraft only seeding for five months would possibly fall between the 9% and 17% values.
- As described above, the estimates of increases in inflow for the Nacimiento drainage using AHOGS sites have been reduced by half.
- The estimates of the value of the water are reasonably accurate.

Table 7-2 provides some estimated costs per acre-foot and benefit/cost ratios. Data in Table 7-2 assumes an operational period of November 15th to April 15th. This table contains estimates of the potential increases in inflow in the two target drainages for both a 9% and a 17% increase in precipitation. For the four AHOGS initial costs of $140,000 are amortized over a five season program the annual expense would be $28,000. This amount has been added to the estimated cost of this option; $108,000 yielding $136,000. For only the aircraft seeding option, the costs are for five months. For the combined ground and aircraft program, the ground seeding cost estimates are for five months and the airborne seeding for three months. The $28,000 annual amortized seasonal expense for the four AHOGS sites has been included in the estimated cost.

Table 7-2 Estimated Costs per Acre-Foot for the Combined Target Areas of Lake San Antonio and Nacimiento Reservoir for a 9% Precipitation Increase

Seeding Mode	Est. Increased Streamflow	Est. Cost	Cost/Ac. Ft.
Four AHOGS Dispensers	23,663*	$136,000	$5.75
Seeding Aircraft	33,958	$268,600	$7.91
Combined Ground and Aircraft	33,958	$312,700	$9.21

* Assumes one-half of the estimated streamflow increases for the Nacimiento drainage from Table 7-1 could be produced using ground based AHOGS units.

Table 7-3 provides the same information as that in Table 7-2 except for an estimated 17% increase in precipitation.

Table 7-3 Estimated Costs per Acre Foot for the Combined Target Areas of Lake San Antonio and Nacimiento Reservoir for a 17% Precipitation Increase

Seeding Mode	Est. Increased Streamflow	Est. Cost	Cost/Ac. Ft.
Four AHOGS Dispensers	44,696*	$136,000	$3.04
Seeding Aircraft	64,141	$268,600	$4.19
Combined Ground and Aircraft	64,141	$312,700	$4.88

* Assumes one-half of the estimated streamflow increases for the Nacimiento drainage from Table 7-1 could be produced using ground based AHOGS units.

To place the results presented in Tables 7-2 and 7-3 in context, the estimated results in Table 7-2 may be more representative of what might be expected using a network of four ground based AHOGS dispensers for a five month period while the estimated results in Table 7-3 may be more representative of what might be expected using a network of four AHOGS dispensers for five months and a seeding aircraft for three months. The expected results of only using a seeding aircraft for five months would possibly fall between the 9% and 17% numbers that are provided in the two tables.

Tables 7-4 and 7-5 provide estimated benefit/cost ratios for different estimated values of water for 9% and 17% precipitation increases, respectively. The data provided in these tables allows for the calculation of any benefit/cost ratio for any estimated value of the water. **The Benefit/Cost ratios do not take into account any losses in the water released from the reservoirs such as evaporation or infiltration into the stream channels below the reservoirs.**

Table 7-4 Estimated Benefit/Cost (B/C) Ratios for the Combined Target Areas of Lake San Antonio and Nacimiento Reservoir for a 9% Precipitation Increase

Seeding Mode	Est. Increased Streamflow	Est. Cost	Est. B/C Ratio, $50/A.F.	Est. B/C Ratio, $100/A.F.	Est. B/C Ratio, $200/A.F.	Est. B/C Ratio, $500/A.F
Four AHOGS Dispensers	23,663 AF	$136,000	8.7 / 1	17.4 / 1	34.8 / 1	87.1 / 1
Seeding Aircraft	33,958 AF	$268,600	6.3 / 1	12.6 / 1	25.3 / 1	63.2 / 1
Combined Ground & Aircraft	33,958 AF	$312,700	5.4 / 1	10.9 / 1	21.7 / 1	54.3 / 1

Table 7-5 Estimated Benefit/Cost (B/C) Ratios for the Combined Target Areas of Lake San Antonio and Nacimiento Reservoir for a 17% Precipitation Increase

Seeding Mode	Est. Increased Streamflow	Est. Cost	Est. B/C Ratio, $50/A.F.	Est. B/C Ratio, $100/A.F.	Est. B/C Ratio, $200/A.F.	Est. B/C Ratio, $500/A.F
Four AHOGS Dispensers	44,696 AF	$136,000	16.4 / 1	32.9 / 1	65.8 / 1	164 / 1
Seeding Aircraft	64,141 AF	$268,600	11.9 / 1	23.9 / 1	47.7 / 1	119 / 1
Combined Ground & Aircraft	64,141 AF	$312,700	10.2 / 1	20.5 / 1	41.0 / 1	102 / 1

8.0 SUMMARY

The Monterey County Water Resources Agency (MCWRA) contacted North American Weather Consultants (NAWC) on August 25, 2016 about the possibility of NAWC performing a feasibility/design study for the Nacimiento Reservoir and San Antonio Reservoir drainages (NRSAR) located in northern San Luis Obispo County and southern Monterey County; respectively. NAWC submitted a proposal to perform such work. A contract was approved to perform this work on November 14, 2016. The stated goal of this program would be to augment the natural precipitation that occurs in the target area to provide additional inflow into these two reservoirs. This work was to be completed in conjunction with a similar study that NAWC conducted for the San Luis Obispo County Flood Control and Water Conservation District. NAWC performed this study feasibility/design study for the Lopez Lake and Salinas Reservoir drainages located in southern San Luis Obispo County.

NAWC reviewed available information, compiled and analyzed data, and developed a proposed program design. Recommendations from the American Society of Civil Engineers (ASCE 2016) publication entitled "Guidelines for Cloud Seeding to Augment Precipitation" include the following:

1. *"When possible, the feasibility study for a program should draw significantly from previous research and well-conducted operational programs that are similar in nature to the proposed program (e.g. similar topography, similar precipitation occurrences, etc.)."*
2. *"The primary purpose of the feasibility study is to answer two questions. First, does it appear that a cloud seeding program could be implemented in the intended target area that would be successful in achieving the stated objectives of the program? Second, are the estimated increases in precipitation expected to produce a positive benefit-cost ratio?"*

NAWC's response to the first recommendation is strongly positive for the proposed target areas. The Santa Barbara II Research program was conducted in two phases (a ground-based and airborne based seeding modes) from 1967-1974. This program demonstrated that significant increases in precipitation could be achieved when convective bands (common features embedded in coastal California winter storms) were seeded with silver iodide. The Santa

Barbara County Water Agency has supported operational seeding programs beginning in 1986 and continuing for most winter seasons to the present (Griffith, et al, 2005). Both ground-based and airborne seeding modes have typically been utilized. A recent evaluation of this operational program indicated average December-March precipitation increases ranging from 9% to 21%. (Griffith, et al, 2015)

Response to the second recommendation is also positive with some caveats as explained later in this section.

The program design calls for the seeding of convective bands using either ground-based remotely operated flare units or airborne seeding with flares or a combination of the two. Both seeding modes have been used for a number of winter seasons on the Santa Barbara County Water Agency program which targets the Twitchell drainage and the Upper Santa Ynez drainage. Three or four ground-based flare units (AHOGS) are proposed. A five month operational period of November 15th to April 15th is recommended.

NAWC typically estimates seasonal increases in precipitation from a proposed program then correlates precipitation to streamflow. Average increases in precipitation are inserted into the regression equation correlating precipitation with streamflow to estimate an average increase in streamflow. If the value of the additional streamflow can be estimated, a benefit/cost ratio can be calculated based upon the estimated costs of conducting the program. This technique was employed in this study. Long-term precipitation gauge stations were correlated with either observed or estimated inflow to the two target reservoirs. Good correlations (as measured by correlation coefficients) were obtained. We then calculated the average inflow values for the two reservoirs. The results obtained from the NAWC evaluation of the Santa Barbara Water Agency program (estimated 9% or 17% increases) were applied to the regression equations to estimate the resulting increases in inflow, based upon the estimated increases in precipitation in an average water year. Table 8-1 summarizes the estimated average increases in inflow.

Table 8- 1 Estimated Streamflow Increases for 9% and 17% Seasonal (November - April) Precipitation Increases

Stream gauge site	Regression for Nacimiento River	Regression for San Antonio River	Total Estimated Increase
9% Precipitation increase	+17.0% (20,590 AF)	+18.5% (13,368 AF)	33,958 AF
17% Precipitation increase	+32.1% (38,891 AF)	+35.0% (25,250 AF)	64,141 AF

Since there is some uncertainty about the effectiveness of the ground-based AHOGS units of necessity being close to the Nacimiento drainage target area (e.g. limited distance between the western drainage boundary and the coastline), NAWC arbitrarily reduced the estimated increases in Table 8-1 by half for some of the calculations that follow. This is not a complication when using airborne seeding since the aircraft may be flown off the coastline.

NAWC calculated the costs of various options in the possible conduct of this program and then calculated the estimated cost per acre-foot of the augmented inflow and the estimated benefit/cost ratios during an average water year. This information is summarized in Table 8-2 (a 9% increase in precipitation) and Table 8-3 (a 17% increase in precipitation). These tables assume an operational period of November 15 to April 15th. When the four AHOGS units initial costs of $140,000 are amortized over a five season program the annual expense would be $28,000. This amount has been added to the estimated cost of this option; $108,000 yielding $136,000. For only the aircraft seeding option, the costs are for five months. For the combined ground and aircraft program, the ground seeding cost estimates are for five months and the airborne seeding for three months.

NAWC asked the Monterey County Water Resources Agency for estimates of the value of additional inflow to the target drainages. The Agency was unable to provide any estimates. The question is what is the value of water in the two target reservoirs for the primary use, which appears to be irrigated agriculture. Lacking any specific estimates, we decided to use a range of possible values. The arbitrary values were $50, $100, $200 and $500 per acre-foot. By combining this information with the data provided in Table 8-1 and the estimated costs, calculations can be made of the potential cost of the additional inflow per acre-foot as well as estimates of benefit/cost ratios.

Table 8-2 Estimated Costs per Acre-Foot for the Combined Target Areas of Lake San Antonio and Nacimiento Reservoir for a 9% Precipitation Increase

Seeding Mode	Est. Increased Streamflow	Est. Cost	Cost/Ac. Ft.
Four AHOGS Dispensers	23,663	$136,000	$5.75
Seeding Aircraft	33,958	$268,600	$7.91
Combined Ground and Aircraft	33,958	$312,700	$9.21

Table 8-3 Estimated Costs per Acre Foot for the Combined Target Areas of Lake San Antonio and Nacimiento Reservoir for a 17% Precipitation Increase

Seeding Mode	Est. Increased Streamflow	Est. Cost	Cost/Ac. Ft.
Four AHOGS Dispensers	44,696	$136,000	$3.04
Seeding Aircraft	64,141	$268,600	$4.19
Combined Ground and Aircraft	64,141	$312,700	$4.88

Tables 8-4 and 8-5 were prepared to provide estimated benefit/cost ratios for 9% and 17% increases in precipitation for a range of assumed values of the additional inflow produced by these increases in precipitation.

Table 8-4 Estimated Benefit/Cost (B.C.) Ratios for the Combined Target Areas of Lake San Antonio and Nacimiento Reservoir for a 9% Precipitation Increase

Seeding Mode	Est. Increased Streamflow	Est. Cost	Est. B.C. Ratio, $50/A.F.	Est. B.C. Ratio, $100/A.F.	Est. B.C. Ratio, $200/A.F.	Est. B.C. Ratio, $500/A.F
Four AHOGS Dispensers	23,663 AF	$136,000	8.7 / 1	17.4 / 1	34.8 / 1	87.1 / 1
Seeding Aircraft	33,958 AF	$268,600	6.3 / 1	12.6 / 1	25.3 / 1	63.2 / 1
Combined Ground & Aircraft	33,958 AF	$312,700	5.4 / 1	10.9 / 1	21.7 / 1	54.3 / 1

Table 8-5 Estimated Benefit/Cost Ratios for the Combined Target Areas of Lake San Antonio and Nacimiento Reservoir for a 17% Precipitation Increase

Seeding Mode	Est. Increased Streamflow	Est. Cost	Est. B.C. Ratio, $50/A.F.	Est. B.C. Ratio, $100/A.F.	Est. B.C. Ratio, $200/A.F.	Est. B.C. Ratio, $500/A.F
Four AHOGS Dispensers	44,696 AF	$136,000	16.4 / 1	32.9 / 1	65.8 / 1	164 / 1
Seeding Aircraft	64,141 AF	$268,600	11.9 / 1	23.9 / 1	47.7 / 1	119 / 1
Combined Ground & Aircraft	64,141 AF	$312,700	10.2 / 1	20.5 / 1	41.0 / 1	102 / 1

To place the results presented in Tables 8-2 through 8-5 in context, the estimated results in Tables 8-2 and 8-4 may be more representative of what might be expected using a network of four ground based AHOGS dispensers for a five month period while the estimated results in Tables 8-3 and 8-5 may be more representative of what might be expected using a network of four AHOGS dispensers for five months and a seeding aircraft for three months (this has frequently been the approach used on a number of previous seasons on the operational Santa Barbara County Water Agency program). The expected results of only using a seeding aircraft for five months would possibly fall between the 9% and 17% numbers that are provided in the four tables. Adding one or two AHOGS units to the four recommended sites in this report would give a broader range of sites to use under a variety of wind directions which would potentially improve the targeting of the seeding effects and therefore likely improve the overall results.

It should be understood that the results in Tables 8-2 through 8-5 are for an **average** water year. Results would be lower in below normal water years and higher in above normal water years. These reservoirs may fill in some water years which would limit the upside of possible increases since seeding would probably end if one or both reservoirs were to fill. **The estimated benefit/cost ratios do not take into account any losses in the water released from the reservoirs such as evaporation or infiltration into the stream channels below the reservoirs.**

As mentioned earlier, these data suggest the potential program would be economically feasible provided that the assumed values of the estimated additional water are reasonably accurate. The ASCE publication (ASCE 2016) cited at the beginning of this section suggests that at least a 5/1 benefit/cost ratio be estimated for a program to be considered economically feasible. The estimated values in Tables 8-4 and 8-5 all exceed this ratio, and in some scenarios are more than an order of magnitude higher for this program. One could take a conservative approach due to the various assumptions and uncertainties in our analysis and divide the estimates in these tables by two or even four and most of the estimated benefit/cost ratios would still be greater than 5/1.

NAWC had previously concluded that the proposed program was technically feasible. **Therefore, the proposed program is considered a feasible means of augmenting the storage in the two proposed target reservoirs since it is concluded that the program would be considered both technically and economically feasible as required by the ASCE 2016 document.**

There would be some upfront costs in establishing a winter cloud seeding program for the Nacimiento Reservoir and San Antonio Reservoir watersheds. Some form of environmental documentation would be required. The other initial expense, should the ground-based seeding mode be implemented, would be conducting site surveys and obtaining leases for three or four AHOGS ground seeding sites. A rough estimate of the cost of completing this task is $15,000. There would also be initial costs to purchase and install these units. We estimate approximately $140,000 to purchase and install four units. A program utilizing only aircraft seeding could be implemented more quickly than a ground-based AHOGS program which may be desirable for various reasons, but NAWC believes the combination of AHOGS ground seeding and aircraft seeding conducted concurrently has the potential to maximize the potential seeding effects by combining these two seeding modes which were tested in the Santa Barbara II phases I and II experimentation.

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GLOSSARY OF RELEVANT METEOROLOGICAL TERMS, ETC.

Advection: Horizontal movement of an air mass. Cold advection describes a colder air mass moving into the area, and warm advection is used to describe an incoming warmer air mass. Dry and moist advection can be used similarly.

Air Mass: A term used to describe a region of the atmosphere with certain defining characteristics. For example, a cold or warm air mass, or a wet or dry air mass. It is a fairly subjective term but is usually used in reference to large (synoptic scale) regions of the atmosphere, both near the surface and/or at mid and upper levels of the atmosphere.

Closed low: A low pressure trough with a closed circulation pattern.

Condensation: Phase change of water vapor into liquid form. This can occur on the surface of objects (such as dew on the grass) or in mid-air (leading to the formation of clouds). Clouds are technically composed of water in liquid form, not water vapor.

Confluent: Wind vectors coming closer together in a two-dimensional frame of reference (opposite of diffluent). The term convergence is also used similarly.

Convective (or convection): Pertains to the development of precipitation areas due to the rising of warmer, moist air through the surrounding air mass. The warmth and moisture contained in a given air mass makes it lighter than colder, dryer air. Convection often leads to small-scale, locally heavy showers or thundershowers. The opposite precipitation type is known as stratiform precipitation.

Convergence: Refers to the converging of wind vectors at a given level of the atmosphere. Low-level convergence (along with upper-level divergence), for instance, is associated with lifting of the air mass which usually leads to development of clouds and precipitation. Low-level divergence (and upper-level convergence) is associated with atmospheric subsidence, which leads to drying and warming.

Deposition: A phase change where water vapor turns directly to solid form (ice). The opposite process is called sublimation.

Dew point: The temperature at which condensation occurs (or would occur) with a given amount of moisture in the air.

Diffluent: Wind vectors spreading further apart in a two-dimensional frame of reference; opposite of confluent.

Entrain: Usually used in reference to the process of a given air mass being ingested into a storm.

Evaporation: Phase change of liquid water into water vapor. Water vapor is usually invisible to the eye.

El Niño: A reference to a particular phase of oceanic and atmospheric temperature and circulation patterns in the tropical Pacific, where the prevailing easterly trade winds weaken or dissipate. Often has an effect on mid-latitude patterns as well, such as increased precipitation in southern portions of the U.S. and decreased precipitation further north. The opposite phase is called La Niña.

Front (or frontal zone): Reference to a temperature boundary with either incoming colder air (cold front) or incoming warmer air (warm front); can sometimes be a reference to a stationary temperature boundary line (stationary front) or a more complex type known as an occluded front (where the temperature change across a boundary can vary in type at different elevations).

Glaciogenic: Ice-forming (aiding the process of ice nucleation); usually used in reference to cloud seeding nuclei.

GMT (or UTC, or Z) time: Greenwich Mean Time, universal time zone corresponding to the time at Greenwich, England. Pacific Standard Time (PST) = GMT – 8 hours; Pacific Daylight Time (PDT) = GMT – 7 hours.

High Pressure (or Ridge): Region of the atmosphere usually accompanied by dry and stable weather; corresponds to a northward bulge of the jet stream on a weather map, and to an anti-cyclonic (clockwise) circulation pattern.

Jet Stream or Upper-Level Jet (sometimes referred to more generally as the storm track): A region of maximum wind speed, usually in the upper atmosphere that usually coincides with the main storm track in the mid-latitudes. This is the area that also typically corresponds to the greatest amount of mid-latitude synoptic-scale storm development.

La Niña: The opposite phase of that known as El Niño in the tropical Pacific. During La Niña the easterly tropical trade winds strengthen and can lead in turn to a strong mid-latitude storm track, which often brings wetter weather to northern portions of the U.S.

Low-pressure (or trough): Region of the atmosphere usually associated with stormy weather; corresponds to a southward dip to the jet stream on a weather map as well as a cyclonic (counter-clockwise) circulation pattern in the Northern Hemisphere.

Mesoscale: Sub-synoptic scale, about 100 miles or less; this is the size scale of more localized weather features (such as thunderstorms or mountain-induced weather processes).

Microphysics: Used in reference to composition and particle types in a cloud.

MSL (Mean Sea Level): Elevation height reference in comparison to sea level.

Nucleation: The process of supercooled water droplets in a cloud turning to ice. This is the process that is aided by cloud seeding. For purposes of cloud seeding, there are three possible types of cloud composition: Liquid (temperature above the freezing point), supercooled (below freezing but still in liquid form), and ice crystals.

Nuclei: Small particles that aid water droplet or ice particle formation in a cloud. This includes both condensation nuclei (which aid in forming a cloud water drop) and freezing nuclei (which aid in turning cloud water drops to the ice phase). Cloud seeding can involve nuclei of either type depending on the situation.

Orographic: Terrain-induced weather processes, such as cloud or precipitation development on the upwind side of a mountain range. Orographic lift refers to the lifting of an air mass as it encounters a mountain range.

Operational Program: A cloud seeding program conducted for the purpose of maximizing precipitation increase in the target area(s), rather than for purposes of conducting research or validating the amount of increase that could be obtained.

Pressure Heights: Units in millibars, or mb. 700 mb corresponds to approximately 10,000 feet above sea level (MSL); 850 mb corresponds to about 5,000 feet MSL; 500 mb corresponds to about 18,000 feet MSL. These are standard height levels that are occasionally referenced, with the 700 mb level most important regarding cloud seeding potential in most of the western U.S.

RAOB: Rawinsonde Observation made by a weather balloon (also known as a sounding).

Reflectivity: The density of returned signal from a radar beam, which is typically bounced back due to interaction with precipitation particles (either frozen or liquid) in the atmosphere. The reflectivity depends on the size, number, and type of particles that the radar beam encounters.

Regression Equation: An equation developed to correlate one or more target and control sites based on historical (in this context, non-seeded) time period(s). This can then be used to estimate cloud seeding effects during the seeded period(s). Both linear regression (correlates average values of control and target areas) and multiple linear regression (correlates the target area average to individual control site values) can be conducted for this purpose.

Ridge (or High Pressure System): Region of the atmosphere usually accompanied by dry and stable weather; corresponds to a northward bulge of the jet stream on a weather map, and to an anti-cyclonic (clockwise) circulation pattern.

Rime (or rime ice): Ice buildup on an object (often on an existing precipitation particle) due to the freezing of supercooled water droplets.

Silver iodide: A compound commonly used in cloud seeding because of the similarity of its molecular structure to that of an ice crystal. This structure helps in the process of nucleation, where supercooled cloud water changes to ice crystal form.

Stratiform: Usually used in reference to precipitation, this implies a large area of precipitation that has a fairly uniform intensity except where influenced by terrain, etc. It is the result of larger-scale (synoptic scale) weather processes, as opposed to convective processes.

Subsidence: The process of a given air mass moving downward in elevation, such as often occurs on the downwind side of a mountain range.

Supercooled: Liquid water (such as tiny cloud droplets) occurring at temperatures below the freezing point (32°F or 0°C).

Synoptic Scale: A scale of hundreds to perhaps 1,000+ miles, the size scale at which high and low pressure systems develop.

Target/control evaluation: An evaluation of seeding effects that compares the seeding target area to well-correlated control sites outside the target area. This requires a sufficient amount of data for a time period prior to any seeding operations, as well as sufficient data for the seeding time period. Typically a linear or multiple linear regression equation is used.

Trough (or low pressure system): Region of the atmosphere usually associated with stormy weather; corresponds to a southward dip to the jet stream on a weather map as well as a cyclonic (counter-clockwise) circulation pattern in the Northern Hemisphere.

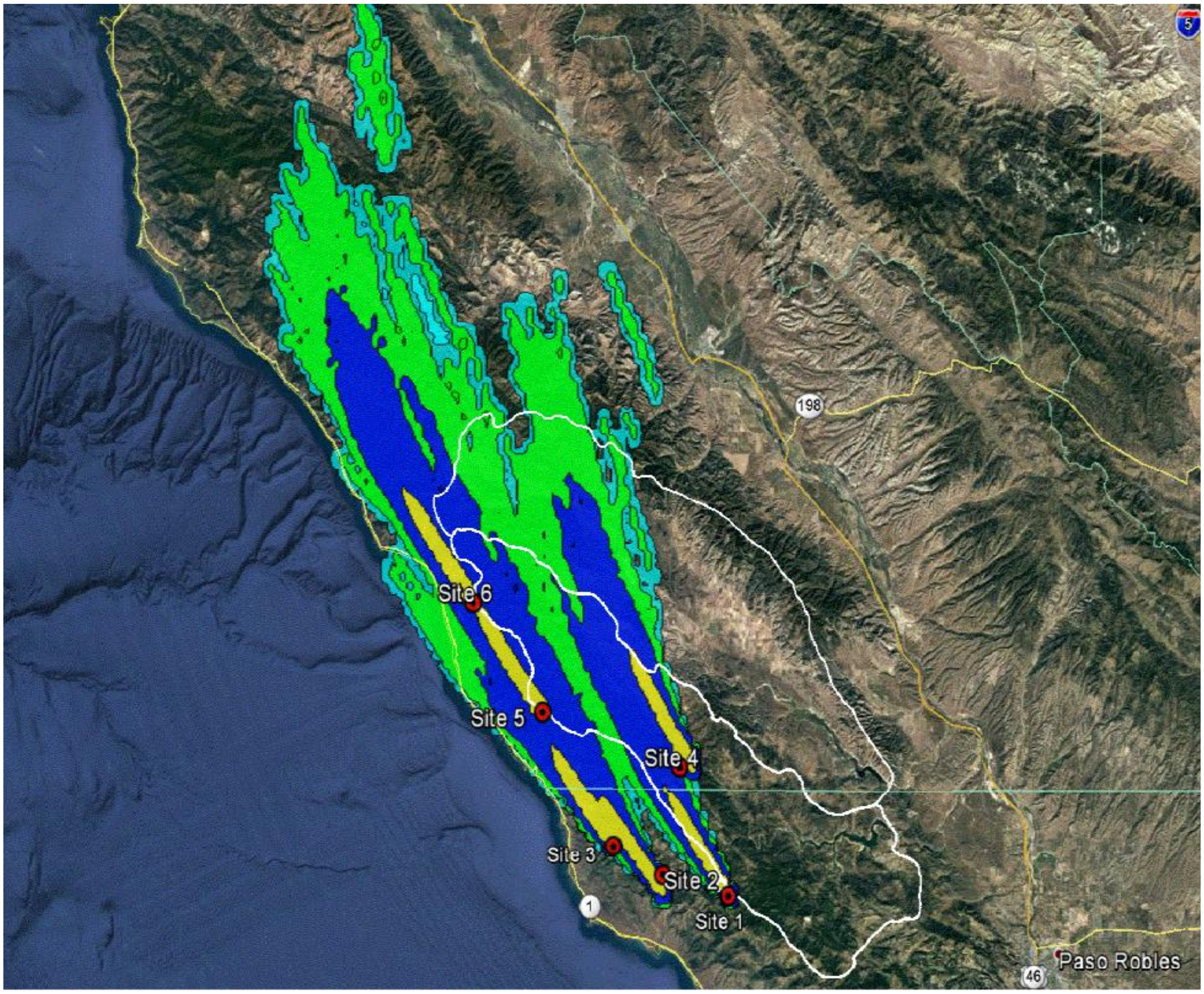
Updraft: Region of rising air within a convective system

UTC (or GMT, or Z) time: Greenwich Mean Time, universal time zone corresponding to the time at Greenwich, England. Pacific Standard Time (PST) = GMT – 8 hours; Pacific Daylight Time (PDT) = GMT – 7 hours.

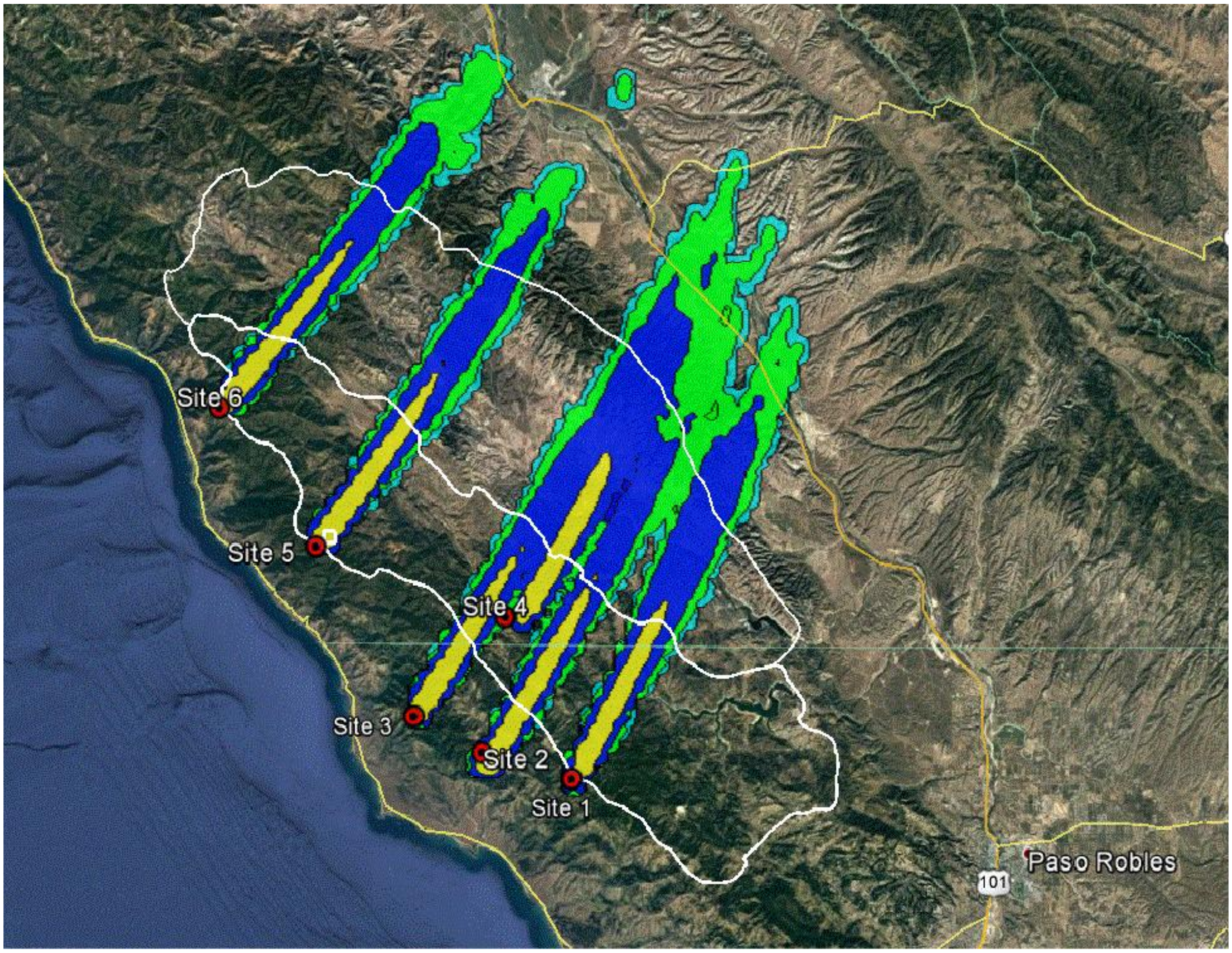
Volume Scan: The composite of multiple radar scans at different levels; each volume scan usually represents about 5-minute time period with the NOAA Doppler Radar systems.

APPENDIX A

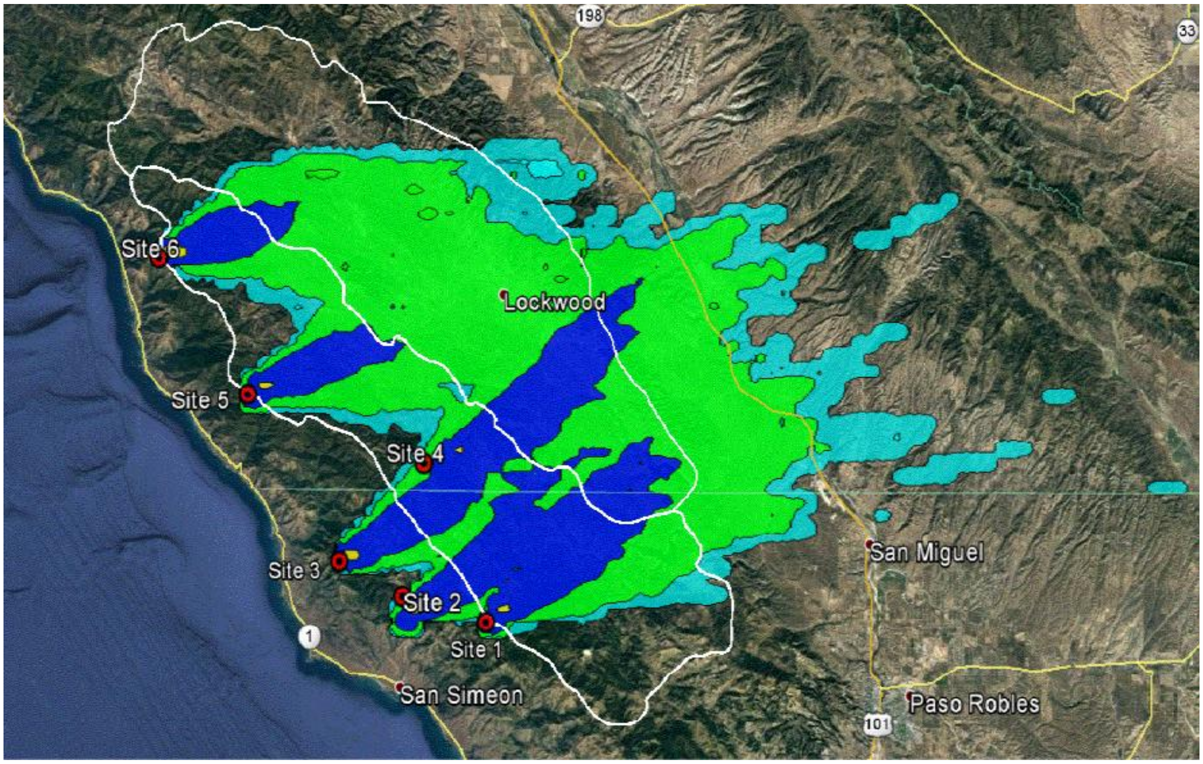
HYSPLIT MODEL SIMULATIONS



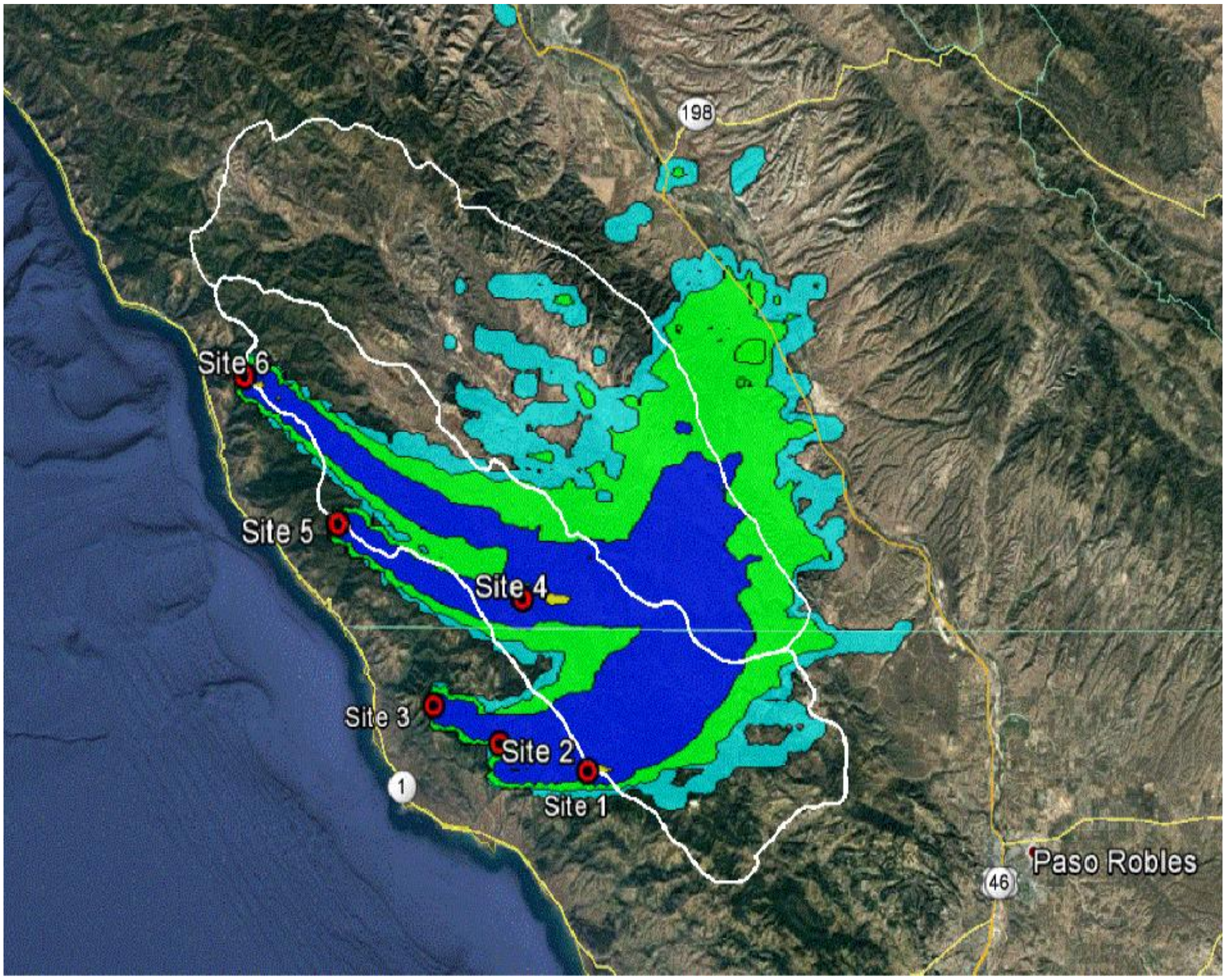
One-hour HYSPLIT simulation of seeding material plumes for possible ground generator locations for a storm period on December 5, 2010; in these plots, yellow (if present) represents the highest concentration of seeding material near the center of the plume; dark blue areas have the next highest concentration, followed by green and light blue shading which depict the weaker concentrations near the edges of the plumes.



One-hour HYSPLIT simulation for a storm period on April 13, 2012



Two-hour HYSPLIT simulation for a storm period on April 1, 2014



One-hour HYSPLIT simulation for a storm period on December 12, 2014

APPENDIX B

DATA USED IN REGRESSION EQUATIONS

Precipitation Data (November – April Totals, Inches)

Water Year	San Antonio Dam	Nacimiento Dam	Atascadero	King City	Mehlschau	San Luis Obispo	Monterey
1967	19.82	24.89	29.98	11.05	21.56	32	27.25
1968	5.17	7.61	10.93	4.79	10.69	16.39	12.23
1969	27.49	29.42	35.63	15.79	26.44	51.41	27.17
1970	9.00	9.41	12.54	7.44	11.09	15.61	15.07
1971	11.45	10.35	15.07	8.53	13.23	19.13	16.01
1972	6.05	6.05	6.81	4.59	6.79	11.81	9.94
1973	21.91	21.24	21.38	17.73	24.31	37.23	24.61
1974	18.31	17.60	18.90	10.89	21.86	28.72	21.12
1975	13.99	12.48	14.71	12.41	14.45	22.19	13.82
1976	4.76	4.81	5.41	3.38	7.27	8.14	7.3
1977	4.09	4.78	6.67	3.46	5.85	7.8	7.16
1978	30.29	28.00	33.60	19.08	30.39	47.42	28.62
1979	16.57	16.36	16.53	11.42	16.81	19.55	18.05
1980	20.47	19.90	26.26	13.21	17.85	30.78	20.93
1981	10.91	11.26	13.96	6.44	15.69	18.48	15.49
1982	14.04	13.78	18.79	10.78	18.78	25.54	25.57
1983	28.06	26.78	35.66	20.79	35.40	43.74	36.28
1984	5.81	6.56	11.10	6.85	9.76	16.25	13.52
1985	8.65	8.63	12.07	8.69	11.44	12.95	14.01
1986	18.84	17.62	23.28	15.87	17.89	28.28	18.07
1987	9.11	8.16	8.53	6.71	12.10	9.85	11.69
1988	10.77	10.89	15.69	7.96	12.91	16.62	10.05
1989	6.76	6.71	10.54	5.73	11.78	15.5	13.94
1990	6.02	5.18	7.55	2.65	5.33	9.11	10.42
1991	13.69	14.08	17.01	11.39	16.22	17.19	13.14
1992	15.58	16.54	19.75	9.95	16.67	21.59	16.16
1993	25.20	21.99	25.66	16.03	20.36	28.85	27.68
1994	9.85	8.56	7.81	6.64	12.24	15.88	12.81
1995	28.46	26.86	28.10	16.98	28.56	39.6	26.05
1996	14.10	15.39	19.04	9.27	17.85	22.98	19.49
1997	11.95	14.49	20.15	10.10	20.73	29.13	20.18

Water Year	San Antonio Dam	Nacimiento Dam	Atascadero	King City	Mehlschau	San Luis Obispo	Monterey
1998	23.84	26.33	30.32	22.21	35.67	40.46	43.26
1999	7.97	8.92	11.76	6.87	15.19	16.35	18.76
2000	11.74	12.65	16.48	9.84	19.51	24.16	19.53
2001	13.81	14.42	16.73	10.70	18.45	22.3	14.54
2002	7.58	8.23	7.42	5.79	9.54	15.27	14.13
2003	12.39	13.05	9.79	9.11	15.66	20.34	17.32
2004	8.66	8.95	8.76	8.97	13.35	15.99	15.63
2005	19.40	20.91	27.69	14.12	21.02	32.26	25.15
2006	13.77	15.22	21.13	10.79	24.14	10.43	24.07
2007	5.04	5.89	7.24	4.22	7.89	7.91	13.07
2008	13.04	12.61	15.39	8.18	15.19	18.36	13.18
2009	9.88	9.68	10.57	5.66	11.59	12.02	16.08
2010	17.04	17.95	20.53	9.59	19.26	17.95	19.72
2011	18.78	20.72	23.25	13.56	24.76	14.92	20.87
2012	8.05	7.55	10.46	5.72	10.78	14.1	12.26
2013	5.09	5.31	7.57	6.30	7.96	12.63	12.54
2014	5.50	5.45	8.86	4.33	6.89	10.12	8.11
2015	9.49	9.70	10.54	7.63	8.36	11.34	13.93
2016	8.83	9.33	14.00	9.58	11.85	17.92	20.6

Streamflow (Total Annual Acre Feet)

Water Year	Nacimiento blw Sapaque	San Antonio nr Lockwood
1967		127303
1968		10703
1969		200384
1970		52687
1971		31724
1972	35929	7426
1973	257788	115069
1974	184814	103412
1975	185812	83022
1976	6109	2832
1977	3965	0
1978	395002	220447
1979	93646	53623
1980	230957	138778

Water Year	Nacimiento blw Sapaque	San Antonio nr Lockwood
1981	51894	29823
1982	173205	91258
1983	450930	329219
1984	68541	45362
1985	54444	19672
1986	212688	194507
1987	24738	18167
1988	26521	14075
1989	23544	9777
1990	10647	3102
1991	75473	31557
1992	72075	31416
1993	245125	137181
1994	33041	10219
1995	248918	172475
1996	128495	85567
1997	194378	147648
1998	326656	207322
1999	61904	27487
2000	133789	72085
2001	84575	42607
2002	44035	28504
2003	104309	47901
2004	50400	26469
2005	255118	149589
2006	165142	108569
2007	40130	11940
2008	97055	46510
2009	36286	21110
2010	193014	99816
2011	204676	127817
2012	26767	13113
2013	43384	27718
2014	7594	1057
2015	37885	9819
2016	56470	19883

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