Feasibility/Design Study for a Winter Cloud Seeding Program in the Lake Lopez and Salinas Reservoir Drainages, California

Prepared for

San Luis Obispo County Flood Control and
Water Conservation District

by

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Report No. WM 16-17
Project No. 15-379

March 2017

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EXECUTIVE SUMMARY

North American Weather Consultants (NAWC) was contracted by the San Luis Obispo County Flood Control and Water Conservation District (District) to conduct a feasibility/design study for a winter cloud seeding program to target the Lopez Lake and Salinas Reservoir (LLSR) drainage basins located in southern San Luis Obispo County, California. A contract was developed between the District and NAWC dated May 5, 2016. 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 followed the ASCE recommendations in the preparation of this study

The design of the program draws heavily from a successful operational program that has been conducted for Santa Barbara County since 1981. The design of this operational program has been based upon the positive effects observed in the Santa Barbara II research program conducted from 1967-1974. Basically, organized convection bands, which are frequently embedded in winter storms that impact San Luis Obispo County, would be seeded with silver iodide from either ground-based sites or a seeding aircraft or both. A five-month, November 15th to April 15th, operational period is recommended.

Long-term precipitation gage stations records were correlated with either observed or estimated inflow to the two target reservoirs. Good correlations (as measured by correlation coefficients) were obtained. NAWC 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 1 summarizes the estimated average increases in inflow.

Table 1 Estimated Streamflow Increases for 9% and 17% Seasonal (Nov-Apr) Precipitation Increases

Stream gage site	Regression for Lopez Dam Inflow	Regression for Lopez Creek Gage
9% Precipitation increase	+17.8%	+13.4%
Inflow to Salinas Dam	+3100 AF	+2334 AF
Inflow to Lopez Dam	+2926 AF	+2203 AF
Total increase for +9% precipitation	6026 AF	+4537 AF
17% Precipitation increase	+33.7%	+26.3%
Inflow to Salinas Dam	+5855 AF	+4579 AF
Inflow to Lopez Dam	+5527 AF	+4322 AF
Total increase for +17% precipitation	11,382 AF	+8901 AF

Cost estimates were developed to conduct a: 1) a ground based 2) an aerial program and 3) a combination program using both seeding modes. Tables 2 and 3 provide estimated costs per acre foot and estimated benefit/cost ratios based upon data from Table 1 and the estimated costs.

Table 2 Estimated Costs per Acre Foot and Estimated Benefit/Cost Ratio for the Combined Target Areas of Lopez and Salinas Reservoirs for a 9% Precipitation Increase

Seeding Mode	Est. Increased Streamfolw	Est. Cost	Cost/Ac. Ft.	Est. Benefit/Cost Ratio
Four AHOGS Dispensers	10,563	$136,000	$12.88	93/1
Seeding Aircraft	10,563	$268,600	$25.43	47/1
Combined Ground and Aircraft	10,563	$312,700	$29.60	41/1

Table 3 Estimated Costs per Acre Foot and Estimated Benefit/Cost Ratio for the Combined Target Areas of Lopez and Salinas Reservoirs for a 17% Precipitation Increase

Seeding Mode	Est. Increased Streamfolw	Est. Cost	Cost/Ac. Ft.	Est. Benefit/Cost Ratio
Four AHOGS Dispensers	20,283	$136,000	$6.71	179/1
Seeding Aircraft	20,283	$268,600	$13.21	91/1
Combined Ground and Aircraft	20,283	$312,700	$15.41	78/1

NAWC's response to the first American Society of Civil Engineers (ASCE 2016) recommendation concerning technical feasibility is strongly positive for the proposed Lopez Lake and Salinas Reservoir program. 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). NAWC's response to the second ASCE recommendation, economic feasibility, is also strongly positive. ASCE suggests a 5/1 or greater benefit/cost ratio for a program to be considered economically feasible. The ratios in Tables 2 and 3 are considerably greater than this 5/1 ratio. **Therefore, the proposed program is considered to be a feasible means of augmenting the storage in the two proposed target reservoirs.**

1.0 INTRODUCTION

The San Luis Obispo County Flood Control and Water Conservation District (District) contacted North American Weather Consultants (NAWC) on February 25, 2016 about the possibility of NAWC performing a feasibility/design study for the Lopez Lake and Salinas Reservoir (LLSR) drainages located in southern San Luis Obispo County. NAWC submitted a proposal to perform such work. A contract was then approved to perform this work on May 5, 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.

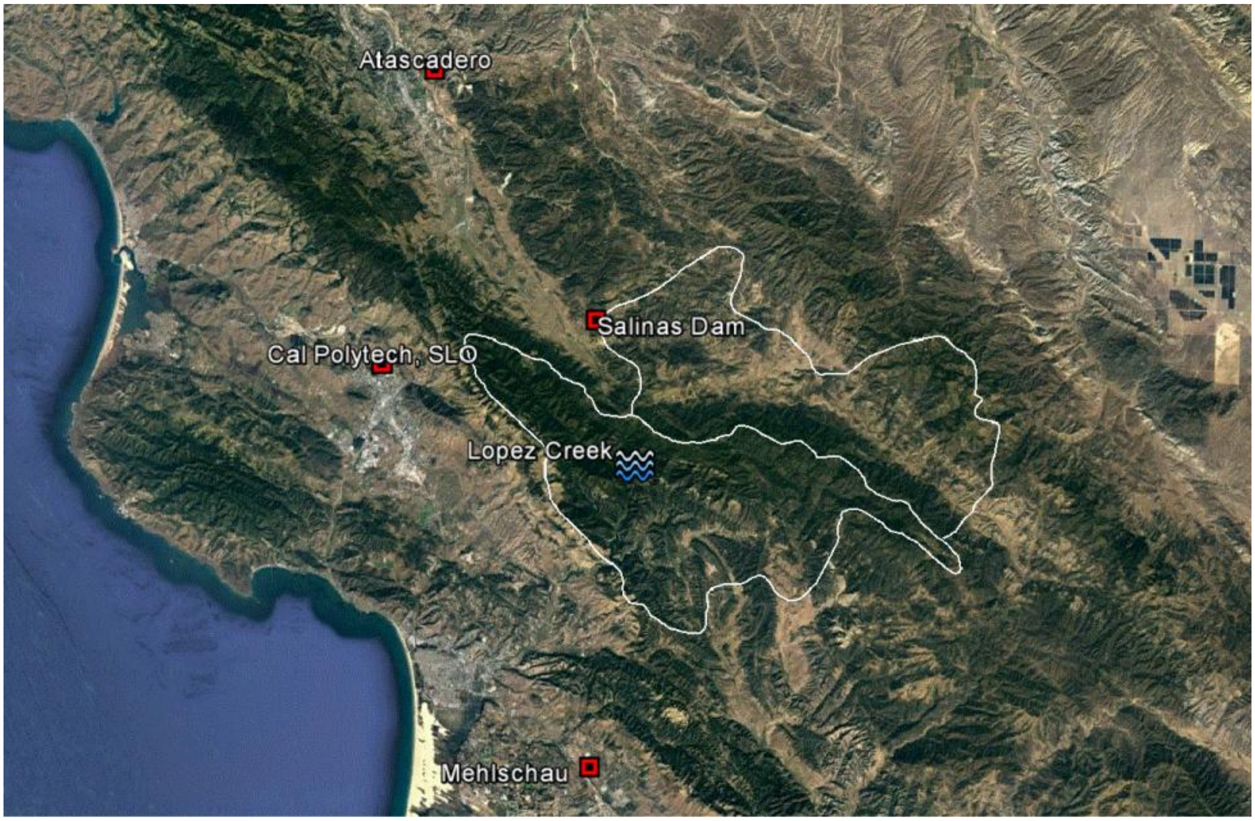


Figure 1.1 Locations of Proposed Target Areas

NAWC was contacted to perform the following tasks:

- 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.

2.0 THEORY OF CLOUD SEEDING FOR PRECIPITATION AUGMENTATION

Clouds form when temperatures in the atmosphere reach saturation, that is, relative humilities 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 has 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 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 was 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.

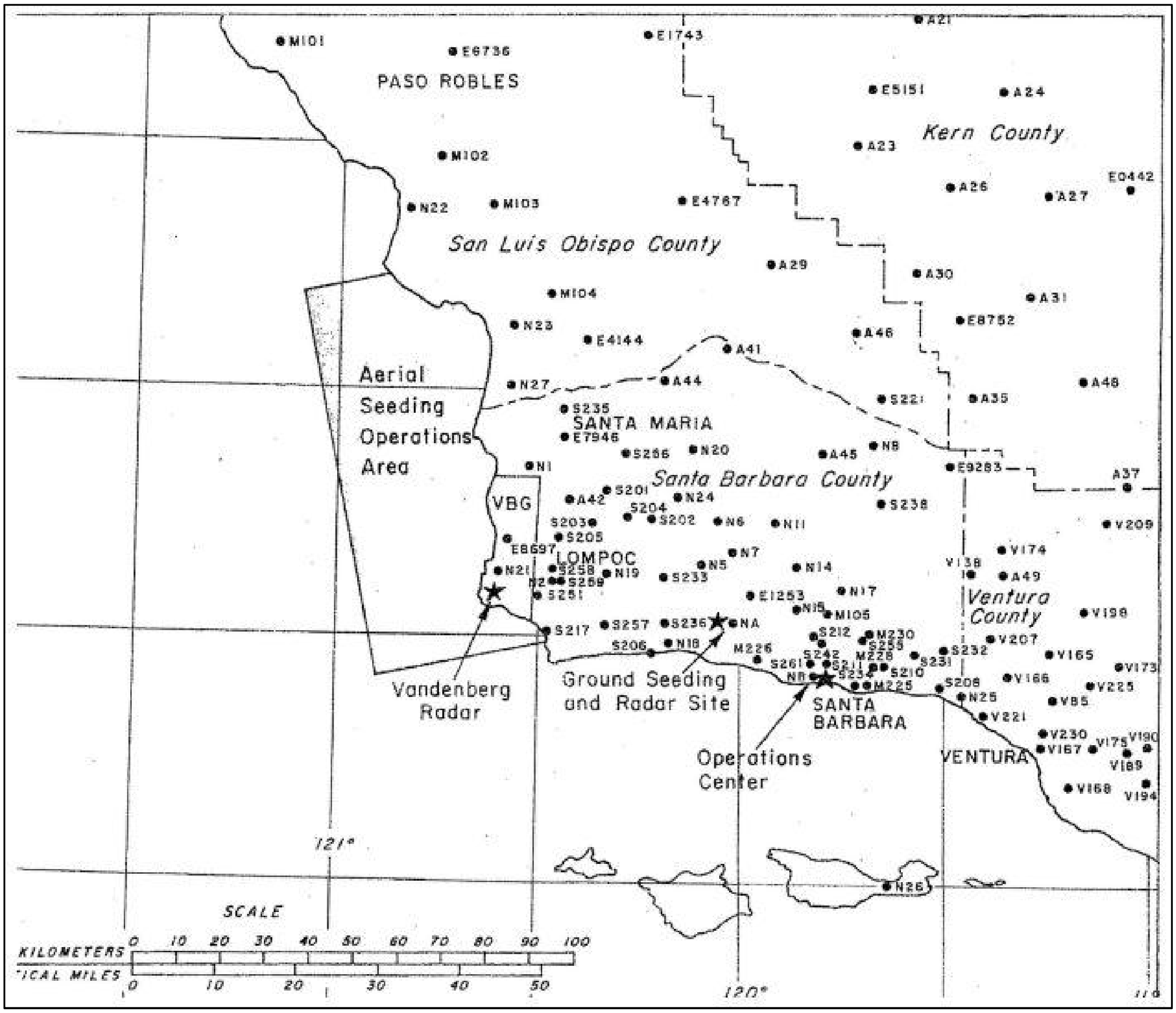


Figure 3.1 Santa Barbara II project map showing rain gauge locations, radar, and seeding sites.

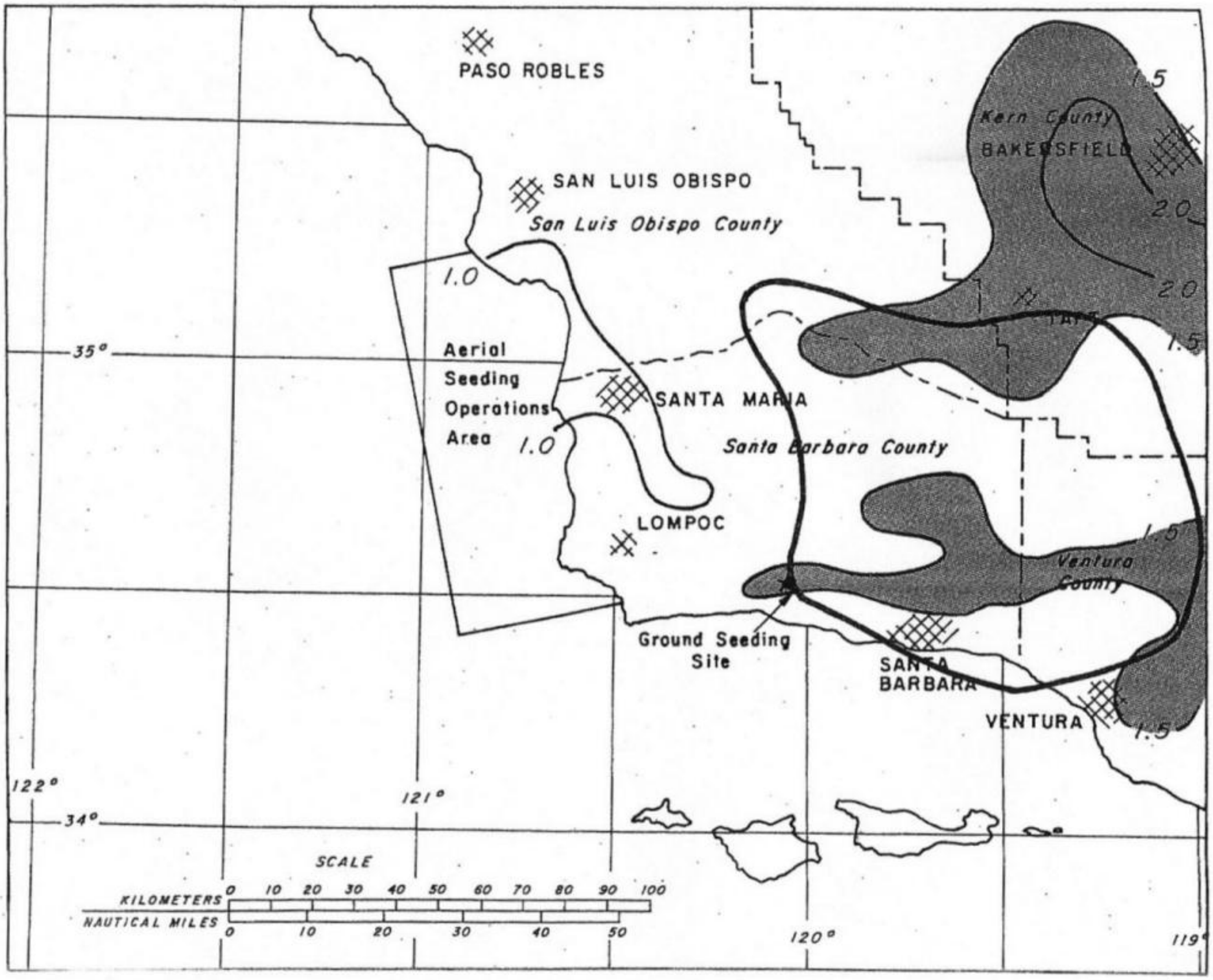


Figure 3.2 Seeded/not-seeded ratios of band precipitation for Phase I ground operations, 1967-71 seasons; 56 seeded and 51 not-seeded bands.

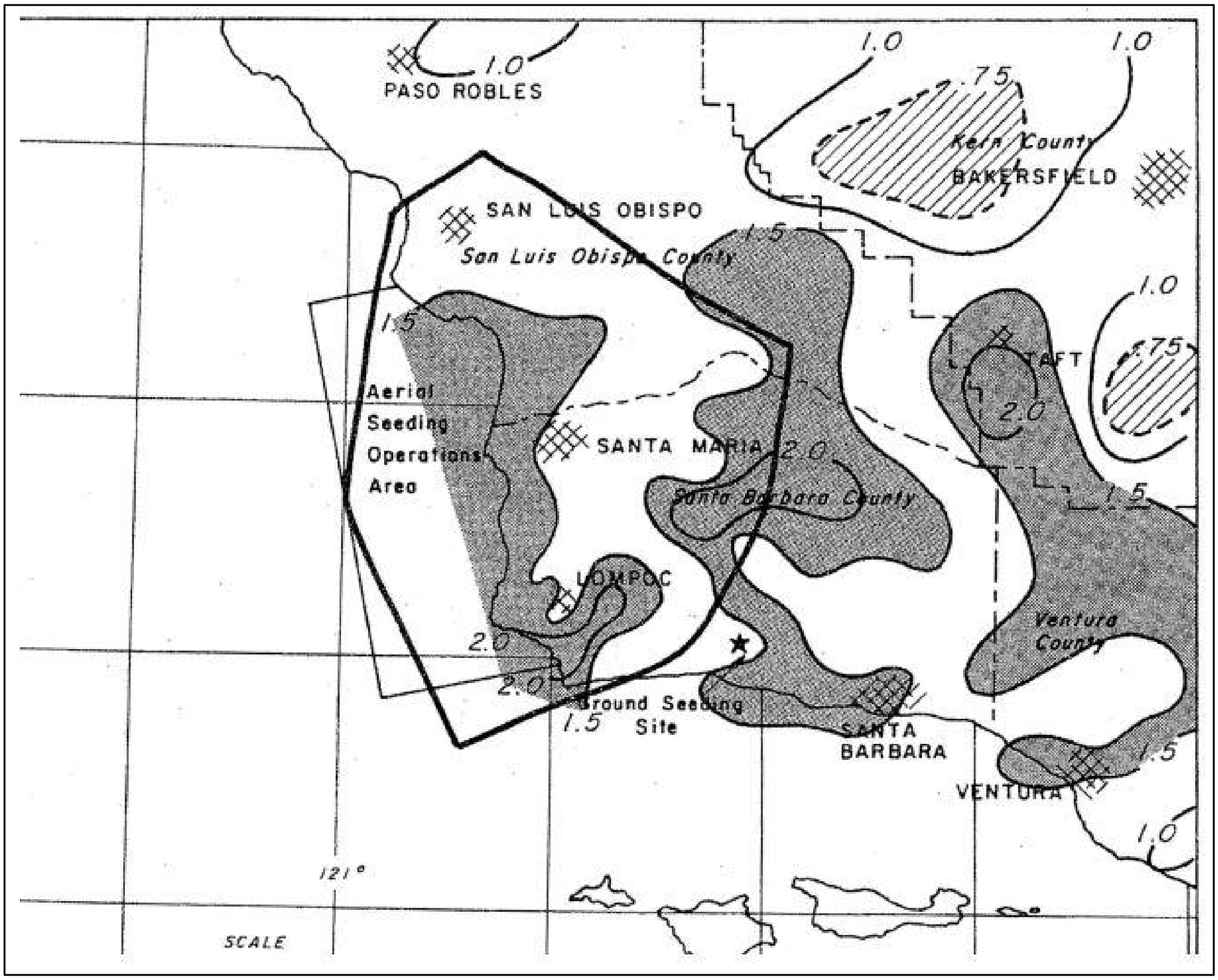


Figure 3.3 Seeded/not-seeded ratios of band precipitation for Phase II aerial operations, 1970-74 seasons; 18 seeded and 27 not-seeded bands.

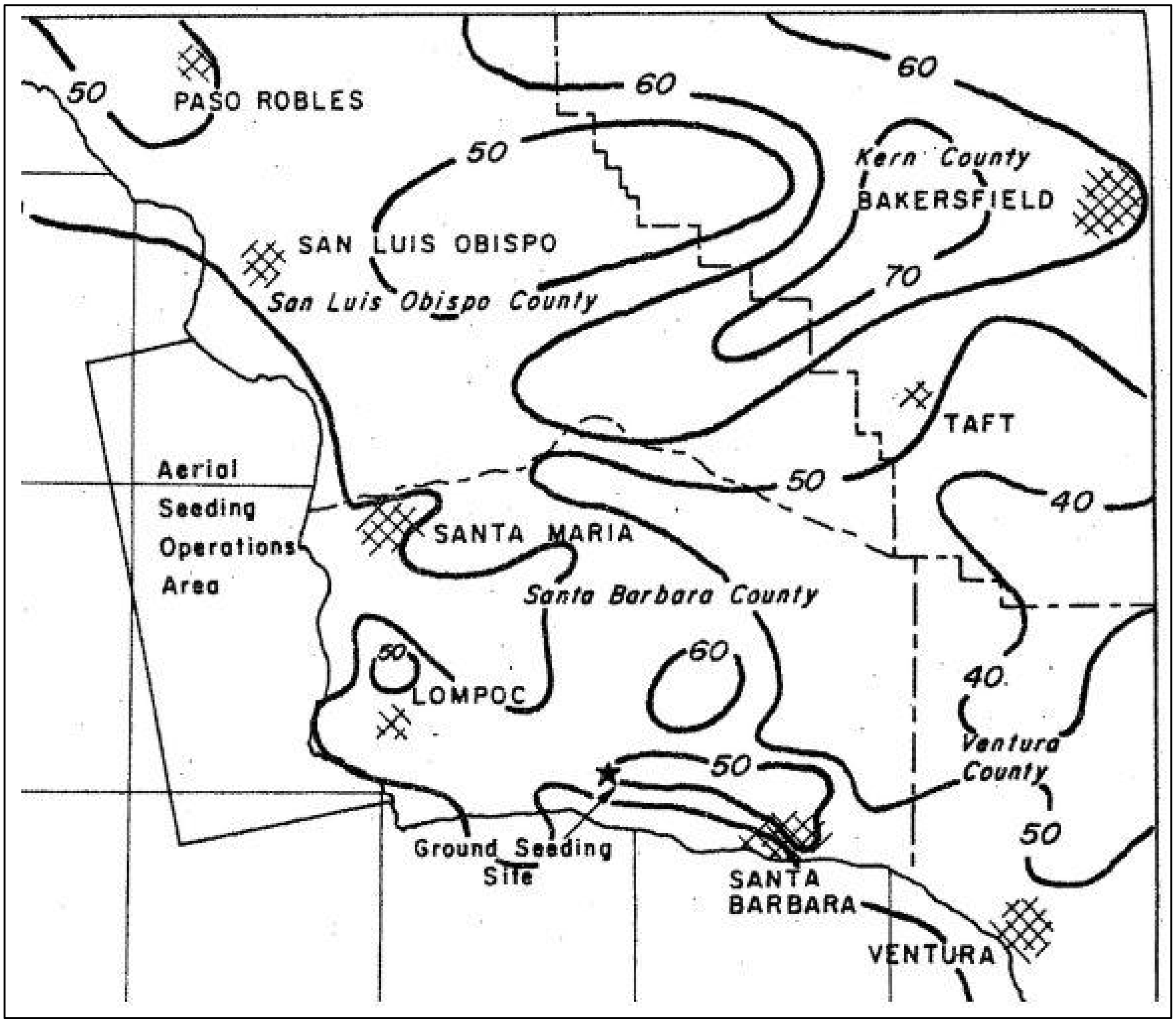
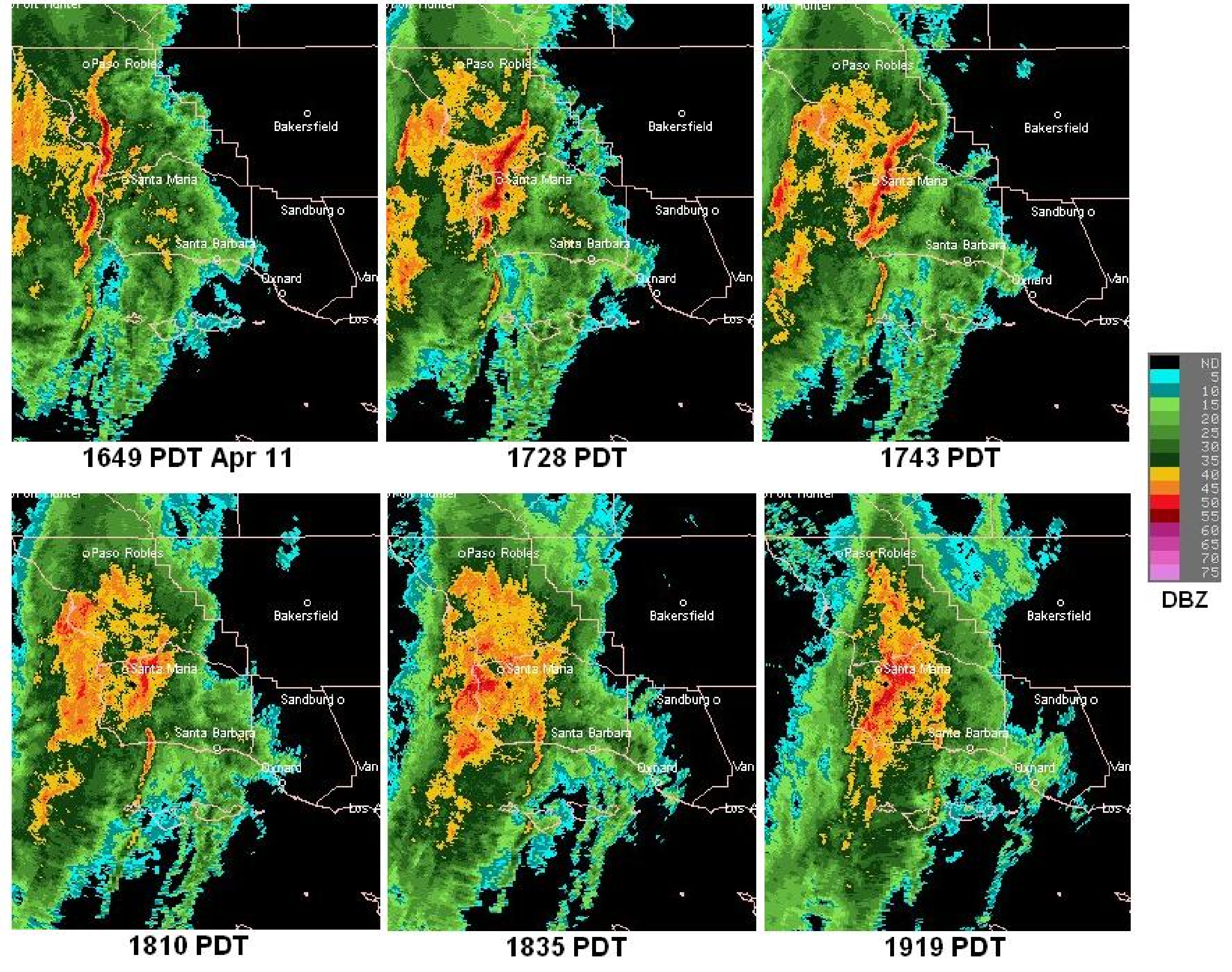


Figure 3.4 Approximate percentage of winter precipitation occurring in convective bands, 1970-74 seasons

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.


1649 PDT Apr 11

1728 PDT

1743 PDT

1810 PDT

1835 PDT

1919 PDT

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 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).

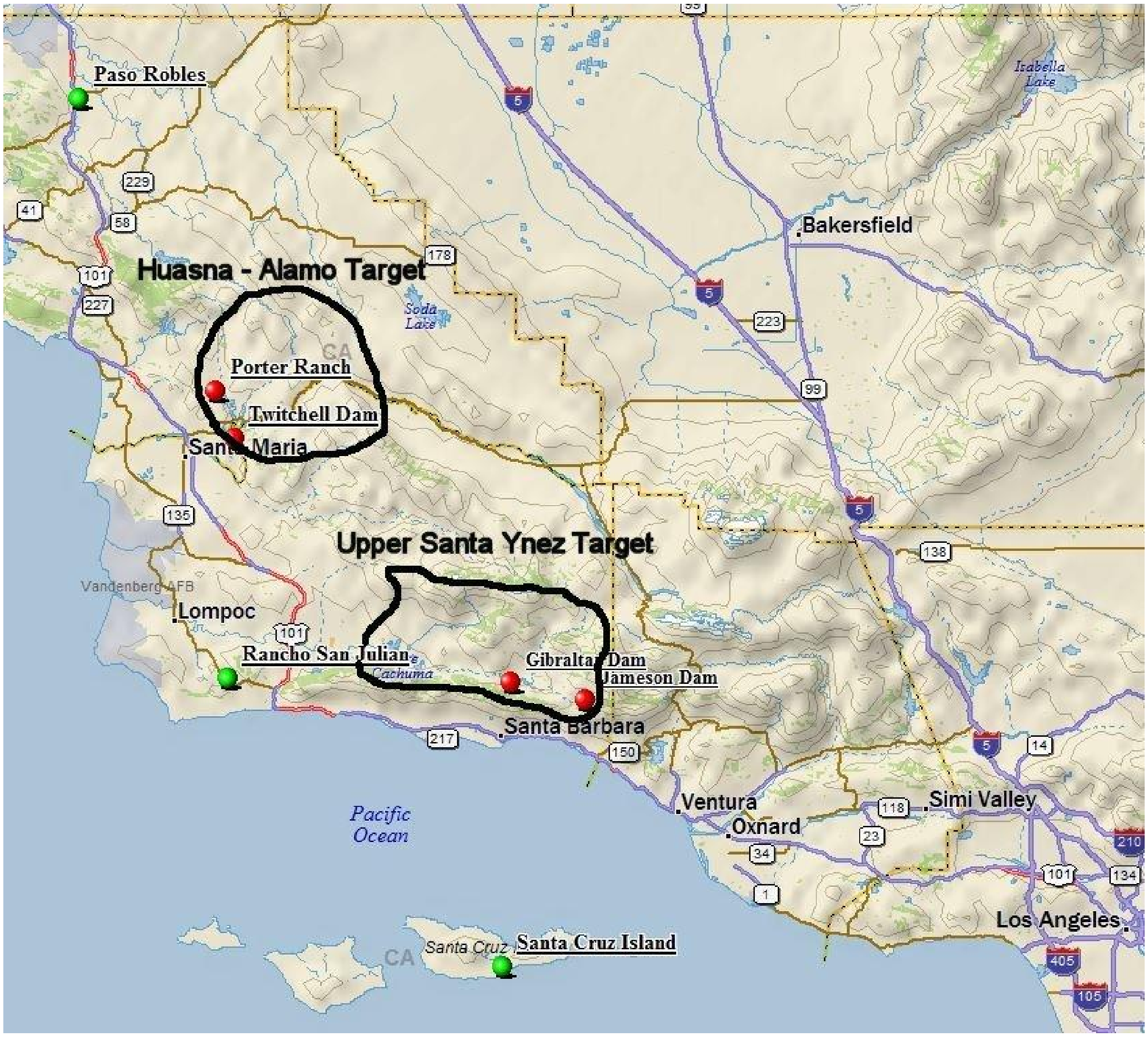


Figure 3.6 Map of the two Cloud Seeding Target Areas and the Locations of Precipitation Control Sites (green) and Target Sites (red).

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

Southern and central portions of California have a Mediterranean type of climate in general, with warm dry summers and wet winters in most areas. The Salinas and Lopez Lake Reservoir drainages lie in the inland portion of San Luis Obispo County, with a semi-arid climate over much of the area and higher precipitation in some mountain locations. Precipitation data were available for a number of stations in this area. Overall, November through April estimates ranged from 9 inches to over 28 inches with Hog Canyon being the driest and Santa Margarita Booster Station the wettest. The majority of the sites have averages between 12-17 inches for roughly 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 32 stations in central and western San Luis Obispo County with long-term records that date back, in several cases to at least the 1950s. The seasonal distribution at these sites should be similar to the Salinas and Lopez Lake Reservoir drainages where only sparse data was available. The multi-station average in Figure 4.1 shows a distinct peak in January. The November – April period accounted for slightly over 90% of the annual precipitation in this composite plot, with the shorter December – March seasonal period accounting for approximately 75% of the annual total. Dividing the totals for the two periods shows that the December – March season accounts for about 83% of the November – April totals. For the Salinas Dam and Lake Lopez watersheds, this means December – March precipitation totals ranging from about 7-8 inches in some of the driest areas to 20-23 inches in the wetter higher elevation areas. While the magnitude of observed precipitation varies considerable 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 quite 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 San Luis Obispo County was conducted in order to classify the temperature and wind characteristics of these bands. Table 4-1 shows the 700 mb data estimates that were obtained. Figure 4.2 is a wind direction frequency plot for these events.

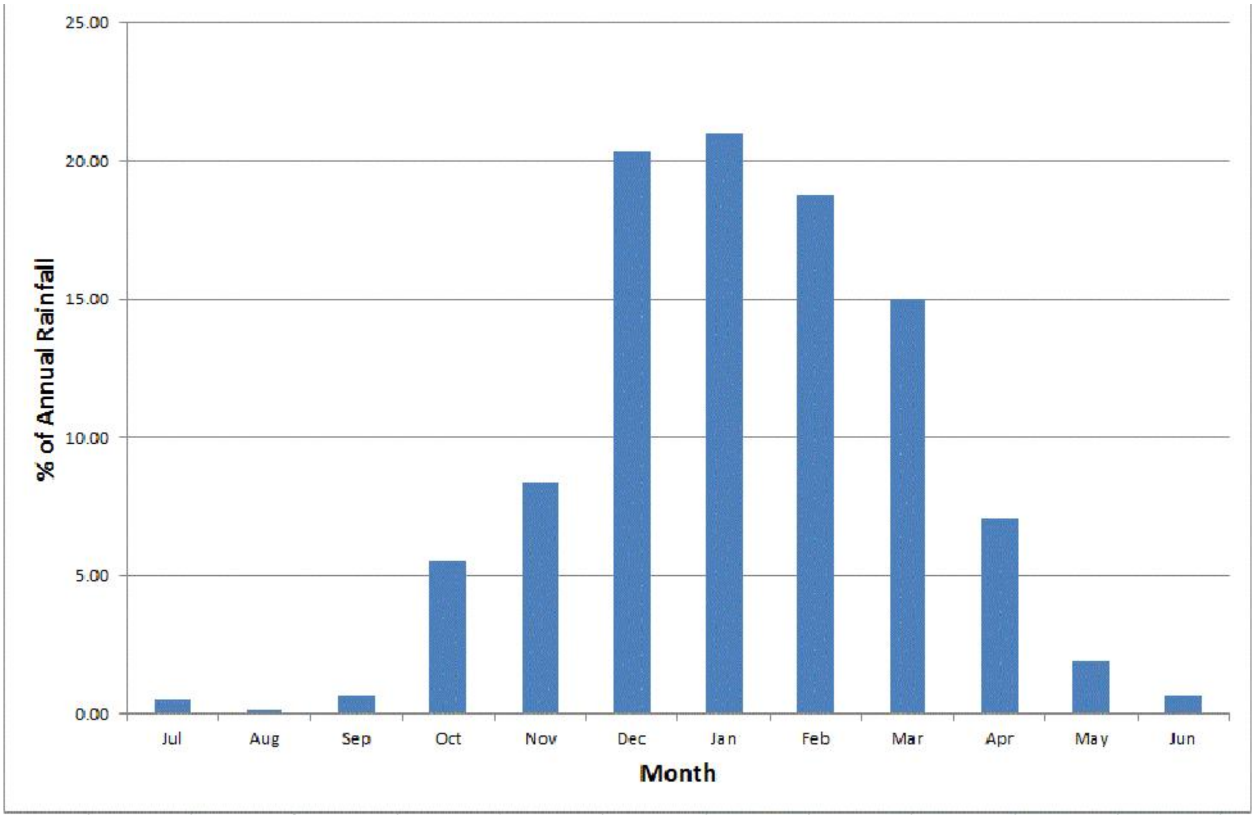


Figure 4.1 Monthly Precipitation Climatology for San Luis Obispo County, Percent of Annual Total

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	1700-2000	-2	-4	35-45	180-220	200
1/1/2011	1300-1600	-5	-5	25-35	260-290	275
1/2/2011	0400-0800	-6	-7	30-40	220-240	230
2/16/2011	0400-0900	-6	-8	35-45	240-270	255
2/18/2011	1100-1600	-6	-6	40-50	220-240	230
2/19/2011	1000-1400	-10	-12	20-30	240-270	255
3/2/2011	0300-0600	0	-1	30-40	250-270	260
3/19/2011	2000-2300	-5	-7	35-45	240-260	250
3/20/2011	0200-0600	-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	0200-0600	-3	-5	40-50	240-260	250
3/25/2012	0100-0400	-3	-6	40-50	200-230	215
4/10-11/2012	2000-0000	-4	-7	20-30	190-230	210
4/13/2012	0400-0700	-8	-9	40-50	230-270	250
12/12/2012	1500-2100	-4	-7	20-30	220-250	235
12/22/2012	0600-1200	-3	-4	35-45	240-260	250
12/25-26/2012	2100-0000	-2	-4	35-45	260-280	270
12/29/2012	0300-0600	-7	-9	10-20	260-280	270
2/19/2013	1400-1700	-8	-10	30-40	250-270	260
3/7/2013	1900-2300	-9	-10	20-30	220-240	230
12/7/2013	0400-0800	-6	-9	35-45	260-280	270
2/2/2014	1100-1500	-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	1800-2200	-6	-10	30-40	250-270	260
4/1/2014	1900-2200	-9	-11	25-35	260-280	270
12/12/2014	0200-0600	-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

Date	Time (PST)	700 mb max T (°C)	700 mb min T (°C)	Wind speed (kts)	Wind direction range	Wind direction average
3/1/2015	1500-1700	-9	-10	10-20	180-220	200
3/2/2015	1000-1400	-9	-9	5-15	210-250	230
4/7/2015	0800-1100	-5	-7	30-40	250-270	260

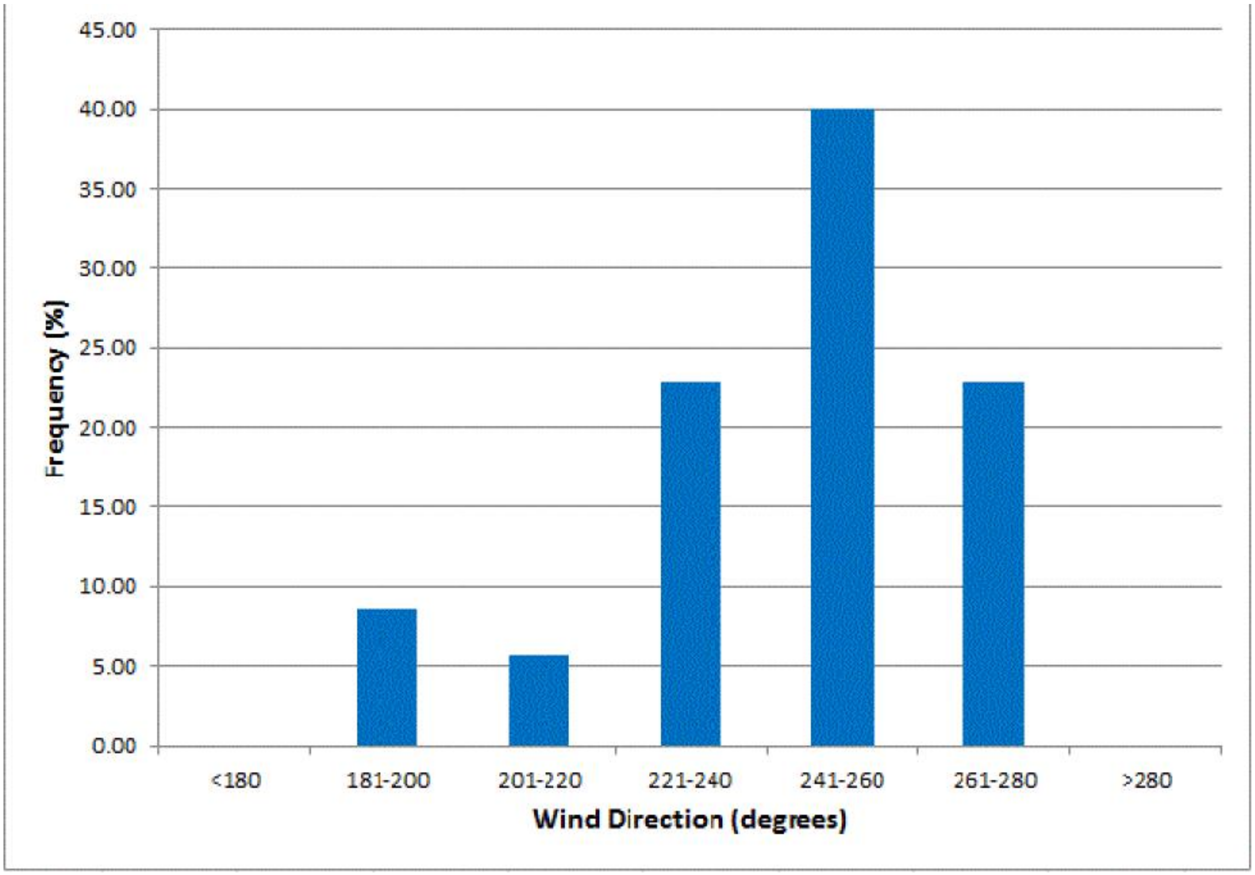


Figure 4.2 700 mb Wind Direction Frequency Plot during Convective Band Passages

Further breakdown of the convective band 700 mb data (estimates) shows that the 700 mb temperature averaged about -4.8°C during the early portion of a frontal convective band passage and around -6.4°C in the latter portion of the band passages, resulting in an overall average of a little colder than -5.5°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 process. 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 (-4.5°C average 700 mb temperature) than late season (March – April) events which averaged -6.4°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 slightly higher during the early season (37.5 knots) compared to the later events (35.8 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, upper 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 be the most favorable. A five-month period of December 15th – April 15th would be a potentially good option, as would a more inclusive six-month period of November – April. From past experience, many November events are quite warm and may not present distinct convective frontal band passages at the latitude of San Luis Obispo County , 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

As stated previously, it has always been 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 to be representative of the operational programs' conditions (i.e., transferable results). The proposed program for the Lopez Lake and Salinas Reservoir (LLSR) 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 LLSR 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 San 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 San Luis Obispo 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 San Ynez drainage target areas. This may be feasible since the targeted clouds are convective bands that tend to first impact San Luis Obispo 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 the 2015-2016 winter season. 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 (“District” = San Luis Obispo County Flood Control and Water Conservation District; “PW” = San Luis Obispo County Public Works)

1)	Constantly 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 ("Alert System" provided by the District), and other information. Such estimates shall be updated regularly as conditions change.
3)	Coordinate with District and PW staff 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 District and PW staff, 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 District and PW 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 District and PW staff prior to project initiation.
9)	Maintain, and submit copies of written operations reports to the District and PW staff 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 combination. It is possible for aircraft operations to be directed from the Contactor’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 on the order of $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 in 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 LLSR target area.

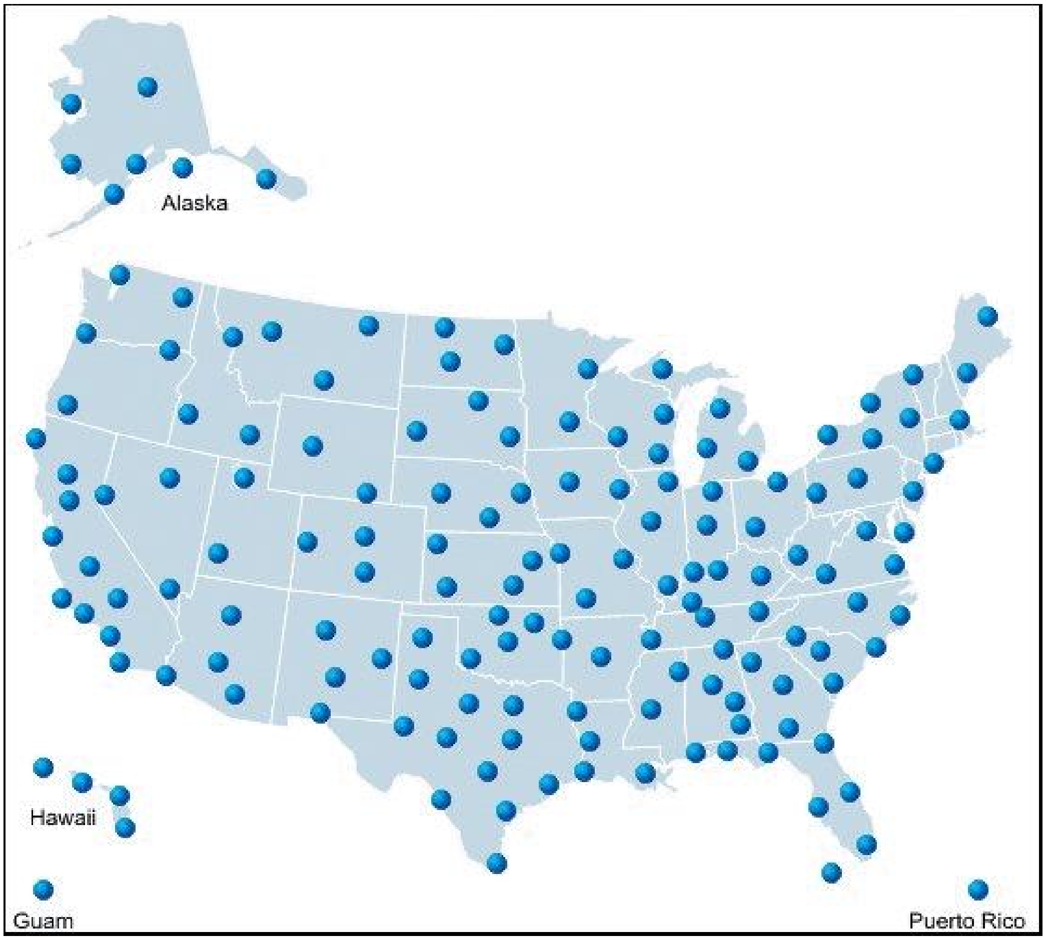


Figure 5.3 US NEXRAD radar locations

NEXRAD data are available in near real time at approximately 5-6 minute intervals through a variety of internet web sites. 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 6,000 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, a short barb 5 nautical miles per hour. A triangular colored barb represents a value of 50 nautical miles per hour. It is seen that the wind speeds were 15-30 knots above the 6,000 foot level during this period.

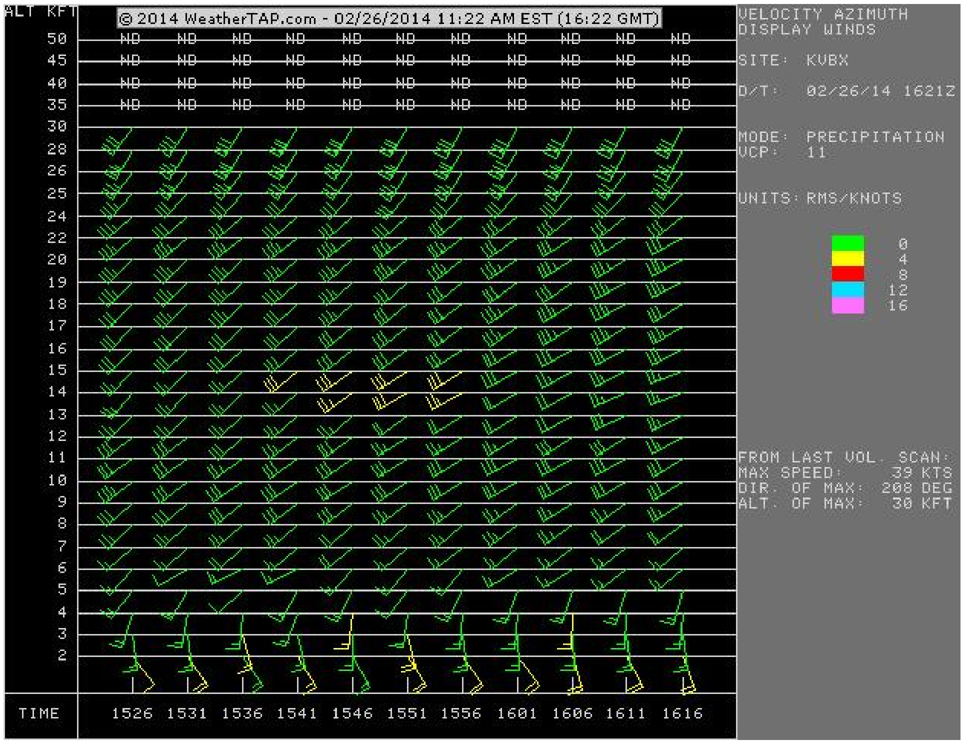


Figure 5.4 Vandenberg AFB Doppler winds, 0726-0816 PST, February 26, 2014

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.

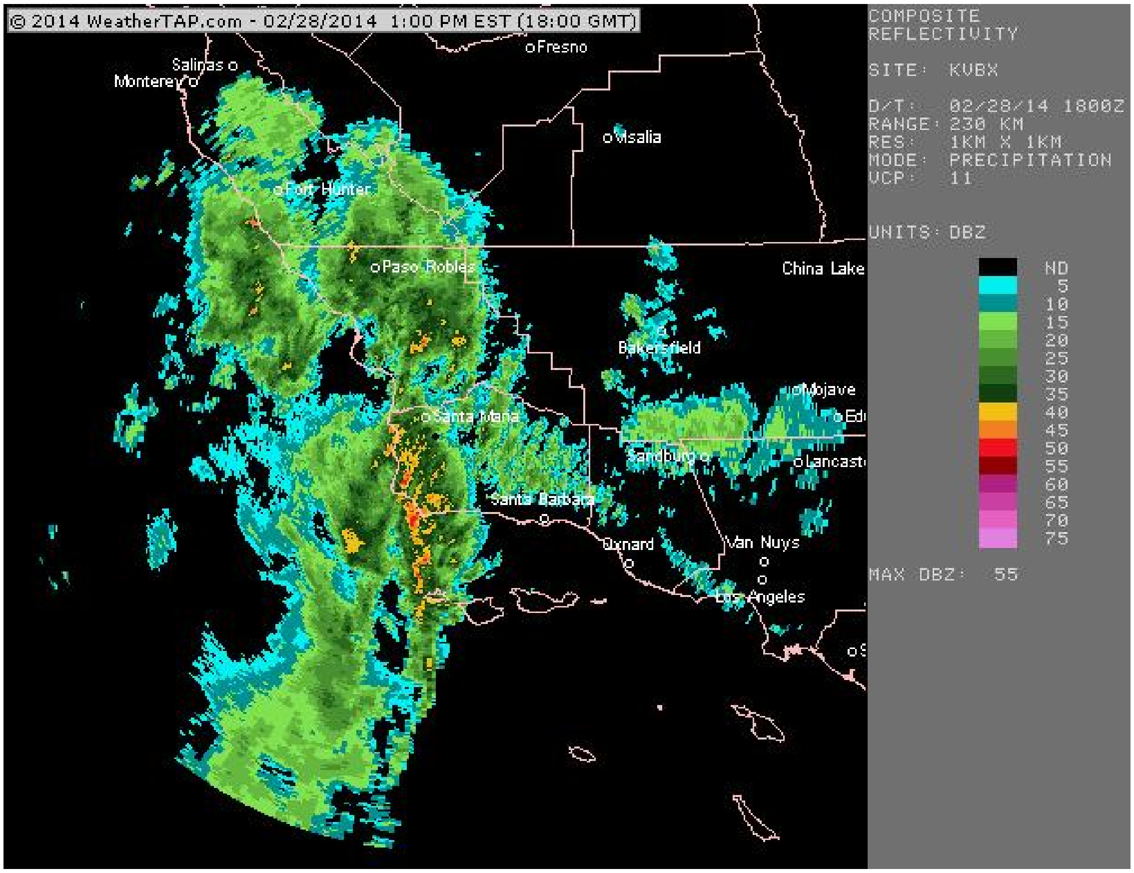


Figure 5.5 Vandenberg AFB radar image at 1000 PST on February 28, 2014

5.4 Ground Seeding Sites

NAWC developed a completely new design for a 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 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 firing flares individually in real time, or to order batch firing 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 LLSR 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.

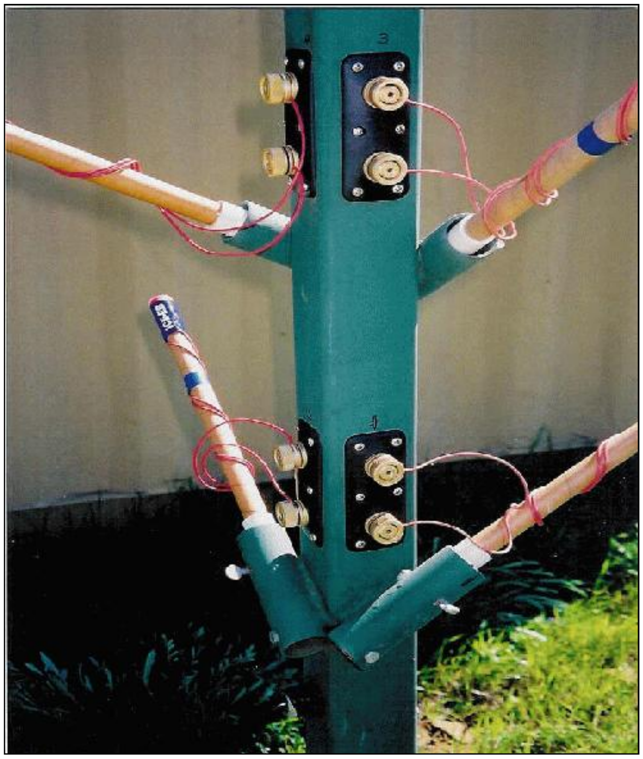


Figure 5.6 Close-up Photo of Flares

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 will emit ~15 grams of fast-acting silver iodide complex seeding material during a burn time of approximately four minutes. 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} AgI)	Corr. Yield (g^{-1} AgI)	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	$2 x 10^{9}$	$1.5 x 10^{11}$
-6	$4 x 10^{10}$	$6 x 10^{12}$
-10	$3 x 10^{13}$	$3 x 10^{13}$

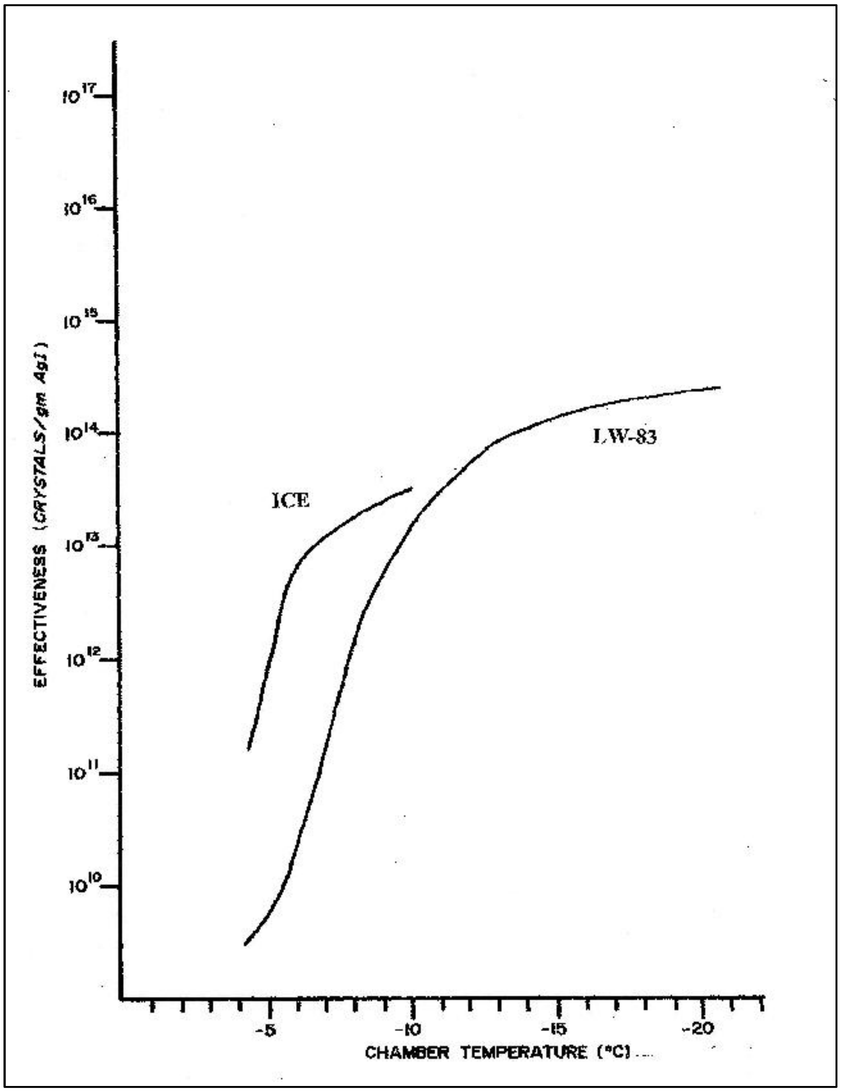


Figure 5.8 Comparison of Effectiveness of the LW-83 Verses the ICE Burn-in-place Flare, CSU Cloud Chamber Results

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 LLSR program.

5.5 Cloud Seeding Aircraft

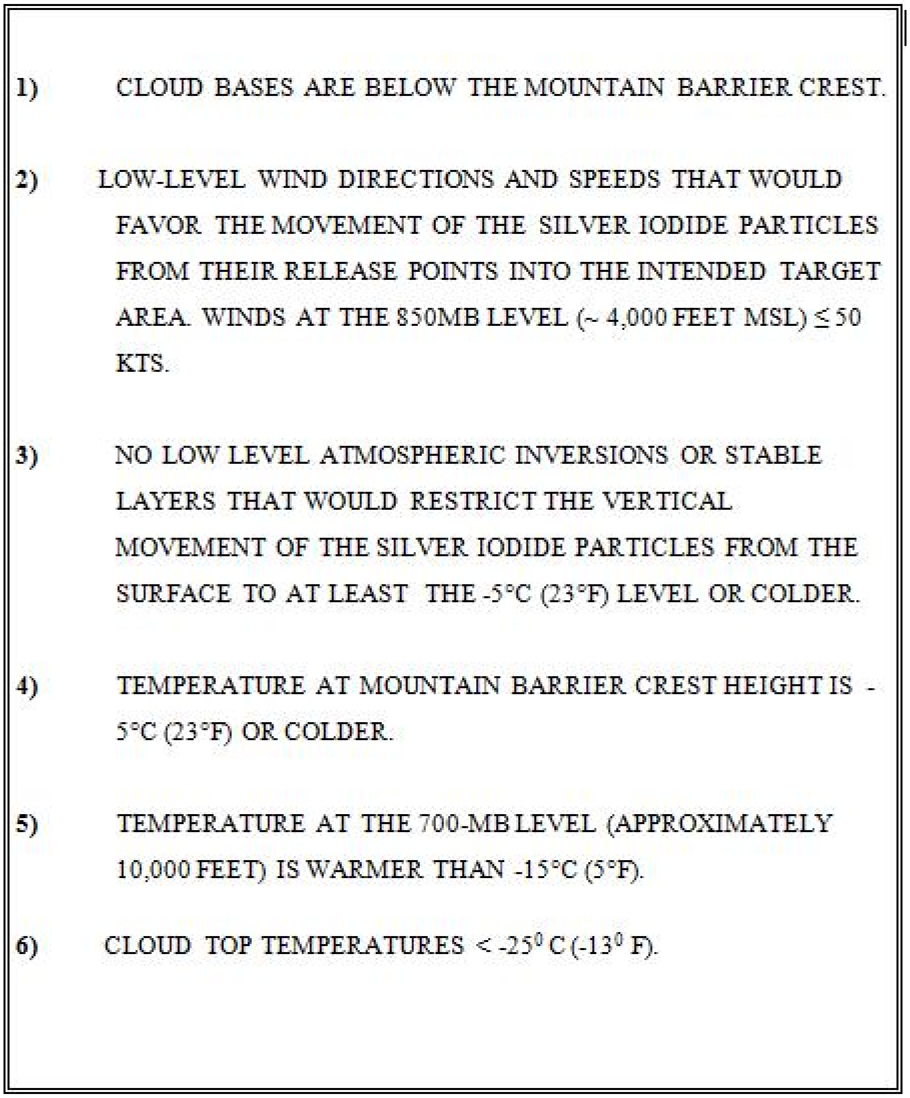
As mentioned earlier, a cloud seeding aircraft could be used to augment the basic ground based flare seeding program. Typical aircraft used on programs of this type include Cessna 340's, Cheyenne II's and King Air 90's. Any seeding aircraft used should be certified for flight in known icing conditions 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 the 6-minute PPI Vandenberg AFB or Los Angeles 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 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 THAT WOULD FAVOR THE MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THEIR RELEASE POINTS INTO THE INTENDED TARGET AREA. WINDS AT THE 850MB LEVEL (~ 4,000 FEET 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 IS -5°C (23°F) OR COLDER.

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

6) CLOUD TOP TEMPERATURES $< -25^0$ C (-13^0 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 like Arroyo Grande Creek. 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 Lopez Lake and Salinas Reservoir 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 District/Agency 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 a number of 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 San Luis Obispo program:

1) The Monterey, San Luis Obispo and Santa Barbara County ALERT weather networks.
2) The National Weather Service surface, upper air and precipitation observations, and predictions from forecast models such as the Global Forecast System (GFS), North American Model (NAM) and Weather Research and Forecasting (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 also 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. These 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 with a 6-minute time resolution from NEXRAD radars. These displays are called Velocity Azimuth Displays (VAD). Customized programs utilizing NWS NEXRAD data will also be used; for example, 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 following 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. The closer the height of the -5°C level is to the ground seeding, the quicker a seeding effect will begin to be produced as the convective elements embedded in the convective bands begin to move over San Luis Obispo County. 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., HYSPLIT).

The National Oceanic and Atmospheric Administration NOAA) runs standard atmospheric models: The North American Model (NAM) and 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. Recently 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 (the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL), the Air Force Weather SBCWA (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, numerics, 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 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.

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 pinpoints 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 is 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.

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.

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. Although the plumes modeled using HYSPLIT may pass over urbanized areas (e.g., San Luis Obispo), there would be no or minimal impact in these areas since the upper portions of the plume are just reaching activation levels over these locations. 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. This model may be available to the public sometime in the future.

5.9 HYSPLIT Modeling for the San Luis Obispo County Seeding Program

The HYSPLIT model was run to assess the potential use of eight ground-based generator sites. Although more or less sites may become realized for any potential program affecting the watersheds in the county, eight locations were used for the purposes of the plume modeling. The eight 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 are reported from 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 eight convective bands that moved through the county during water years 2010-2014. The time of band passage through the proposed target area was estimated from the time of convective band passage through Santa Barbara 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	180-210	Approaching trough
01/02/2011	1200-1600	-6 to -7	30-40	220-240	Upper low
02/19/2011	1800-2200	-10 to -12	20-30	240-270	Trough/Upper low
01/21/2012	0700-1100	+1	45-55	260-280	Weak trough
04/10/2012	0400-0800	-4 to -7	20-30	190-230	Deep trough
12/22/2012	1400-1800	-3 to -4	35-45	240-260	Weak trough
02/02/2014	1900-2300	-7 to -9	15-25	260-280	Upper low
12/12/2014	1000-1400	-4 to -7	40-50	220-240	Upper trough

The map in Figure 5.9 illustrates the theoretical target area, outlined in white and eight 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	35.239°N	120.791°W	1490
2	35.208°N	120.737°W	1408
3	35.172°N	120.603°W	450
4	35.124°N	120.503°W	964
5	35.067°N	120.440°W	1500
6	35.049°N	120.285°W	1278
7	35.240°N	120.398°W	2033
8	35.226°N	120.308°W	2078

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 southern 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 eight potential ground-based sites when a convective band was moving into the proposed target area. These predictions are for one hour of transport. Plumes would extend further for two hour predictions and beyond.

If four sites were installed and the site logistics were favorable, sites 3, 4, 5, and 7 are recommended.

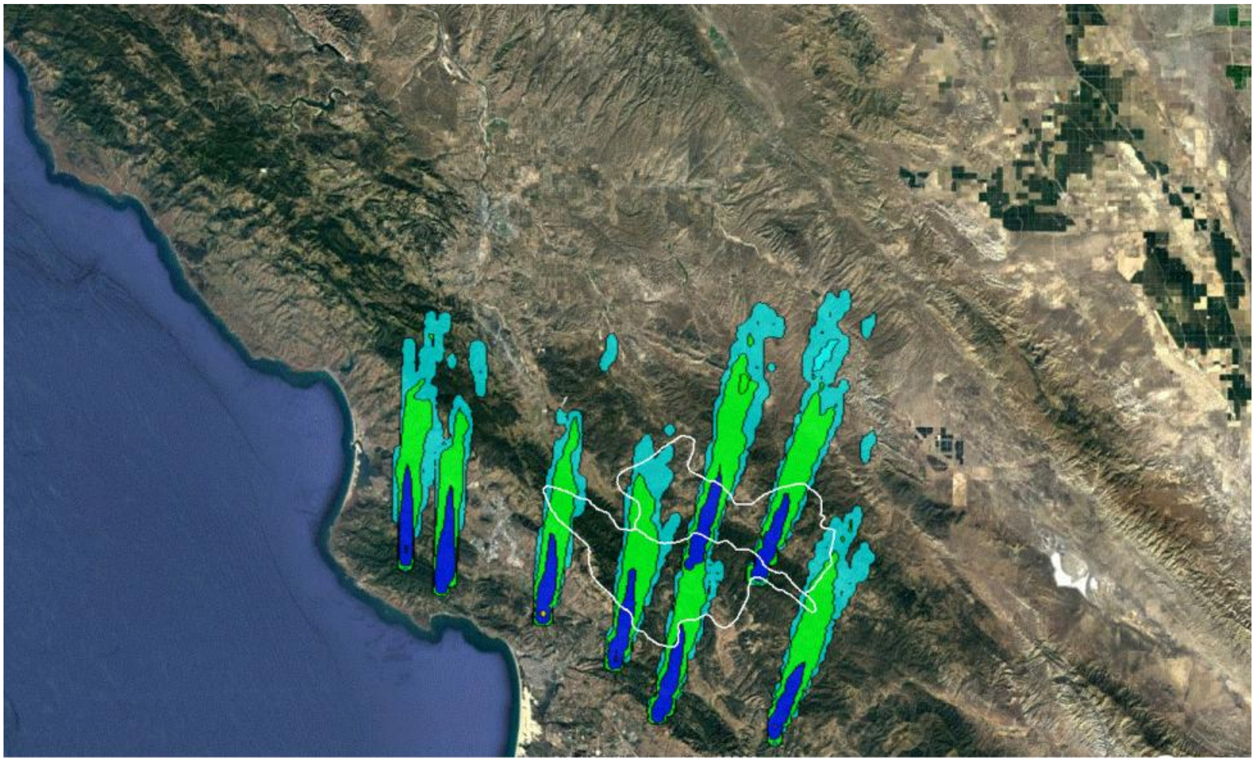


Figure 5.10 One-hour HYSPLIT run for February 2, 2014 during the Initial Passage of a Convective Band Associated with an Upper Low along the Coast

6.0 SEEDING AND STREAMFLOW INCREASE ESTIMATES

The seasonal seeding precipitation increase estimates were determined to be approximately in between 9% and 17% (Griffith, et al, 2015). Regression equations were developed relating stream gauge data versus seasonal (November – April) precipitation for available sites in the area. Data for the annual Salinas Dam and Lopez Dam inflow were obtained from San Luis Obispo County personnel, as well as the San Luis Obispo County Water website. Lopez Creek streamflow data (used in the regression analysis) is available on the United State Geological Survey (USGS) website and were obtained for the 1969-2015 water years for Lopez Creek near Arroyo Grande (USGS site # 11141280). The data from the Lopez Creek gauge, as well as total inflow data for Lopez Dam for water years 1969-2009 (excluding water year 2000), and total inflow to Salinas Dam for the 1988-2016 water years, were correlated with eight precipitation gauge sites containing long periods of record. The average annual inflow values based on the available data periods were 17,399 acre-feet (Salinas Dam) and 16,423 acre-feet (Lopez Dam). Four of the eight precipitation gauge sites (Salinas Dam, San Luis Obispo Polytech, Atascadero, and Mehlschau) were selected as having the best overall correlation to the Lopez Creek stream gauge data and the inflow to the two reservoirs. Appendix C contains the raw data sets used in the development of the precipitation/streamflow regressions. Estimates were made for a few missing monthly precipitation totals, using data from nearby sites and were adjusted by the ratio of the long-term averages for that month. These adjustments had a very 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.

Table 6-1 Locations of Precipitation and Streamflow Gauge Data

Precipitation Site	**Latitude**	**Longitude**
Salinas Dam	35° 20’	-120° 30’
San Luis Obispo Polytech	35° 18’	-120° 40’
Atascadero Mutual Water	35° 29’	-120° 38’
Mehlschau #38	35° 04’	-120° 30’
Streamflow Site	**Latitude**	**Longitude**
Lopez Creek	35° 14’	-120° 28’
Lopez Dam inflow	N/A	N/A
Salinas Dam inflow	N/A	N/A

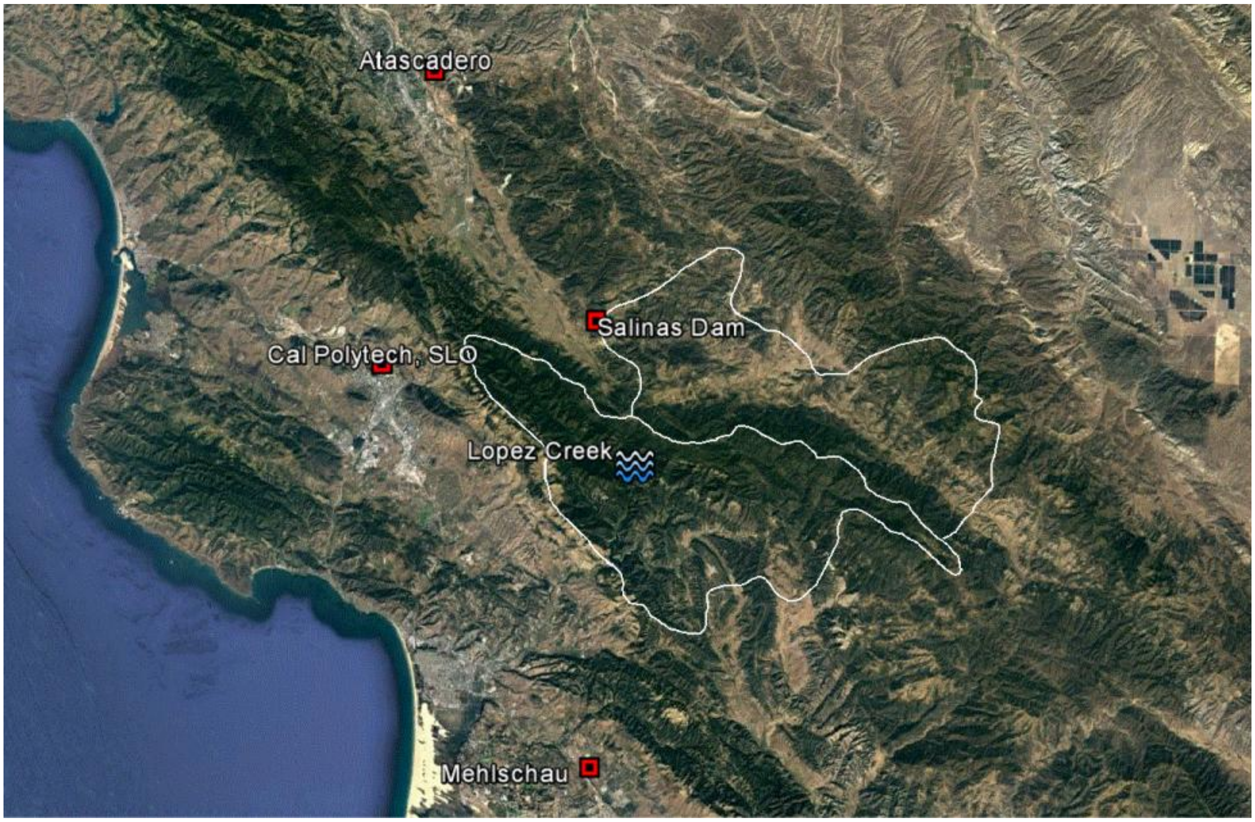


Figure 6.1 Precipitation gauges (squares) and Lopez Creek stream gauge; watersheds outlined in white

The regression equations provide estimates of streamflow increases based on a given precipitation increase. 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. Two of the regression equations developed, those based on Lopez Creek and Lopez Dam inflow, yielded somewhat comparable and reasonable results while the third, which was based on the Salinas Dam inflow during a shorter historical period, was somewhat of an outlier showing what we consider to be unrealistically high percentage increases. For this reason, only results from the Lopez Creek and Lopez Dam inflow regression equations were utilized, although these equations can reasonably be applied to the Salinas Dam inflow as well since it is in the same overall geographic region. The regression equations are shown below and the resulting estimated streamflow increases in Table 6-2 based on estimated seasonal precipitation increases of 9% or 17% due to seeding. For a 9% increase in seasonal precipitation the estimated increases in inflow for both Salinas and Lopez Dams ranged from 4,537 acre-feet and 6026 acre-feet. For a 17% increase in precipitation, the total estimated inflow increase ranged from 8,901 acre-feet to 11,382 acre-feet. The two regression equations used in this analysis are provided below:

- **Equation 1 Regression equation for Lopez Dam inflow:**

  $Y = 1694(X) -16,089$

  where Y is <u>annual</u> total streamflow in acre-feet, and X is the average of the precipitation gauge seasonal (November – April) totals in inches. The offset term in the equation (-16,089) is in acre-feet. The r-value for equation 1 is 0.85.

- **Equation 2 Regression equation for Lopez Creek gauge:**

  $Y = 601.8(X) – 4,291$

  where Y is the <u>annual</u> total streamflow in acre-feet, and X is the average of the precipitation gauge seasonal (November – April) totals in inches. The offset term in the equation (-4,291) is in acre-feet. The r-value for equation 2 is 0.91.

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

Stream gage site	Regression for Lopez Dam Inflow (Eq.1)	Regression for Lopez Creek Gage (Eq.2)
9% Precipitation increase	+17.8%	+13.4%
Inflow to Salinas Dam	+3100 AF	+2334 AF
Inflow to Lopez Dam	+2926 AF	+2203 AF
Total increase for +9% precipitation	6026 AF	+4537 AF
17% Precipitation increase	+33.7%	+26.3%
Inflow to Salinas Dam	+5855 AF	+4579 AF
Inflow to Lopez Dam	+5527 AF	+4322 AF
Total increase for +17% precipitation	11,382 AF	+8901 AF

<u>We have not attempted to estimate what the difference in precipitation increases might be through only using ground-based seeding, only airborne or a combination of the two seeding modes</u>. Both seeding modes have typically been used on the Santa Barbara program often in the same seeded seasons although ground-based seeding has typically been conducted for five moth periods where airborne seeding, due to its expense, has been conducted for three month periods. Perhaps a crude approximation could be made by assuming ~9% precipitation increases could be obtained using only ground-based equipment and ~17% increases could be obtained by using a combination of ground-based and airborne seeding. The information provided in Table 6-2 will be used in the next section to estimate the potential benefit/cost ratios from the conduct of a seeding program.

7.0 ESTIMATED PROGRAM COSTS AND BENEFIT/COST ESTIMATES

There could be some upfront costs in establishing a winter cloud seeding program for the Lopez and Salinas Drainages. For example, should the ground-based seeding mode be implemented, there would tasks to be completed including 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 District 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

Only an airborne 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 gauge site	Regression for Lopez Dam Inflow	Regression for Lopez Creek Gauge	Total Streamflow Increases for Both Drainages
9% Precipitation increase	+17.8%	+13.4%	
Inflow to Salinas Dam	+3100 AF	+2334 AF	5434
Inflow to Lopez Dam	+2926 AF	+2203 AF	5129
Total increase for +9% precipitation	6026 AF	+4537 AF	10,563
17% Precipitation increase	+33.7%	+26.3%	
Inflow to Salinas Dam	+5855 AF	+4579 AF	10,434
Inflow to Lopez Dam	+5527 AF	+4322 AF	9,829
Total increase for +17% precipitation	11,382 AF	+8901 AF	20,283

The District provided NAWC with the estimated value of additional inflow to the target drainages. This estimated value was $1,200/A.F. but there is some uncertainty with this value due to assumptions that need to be made such as the end users of the augmented runoff (e.g. value may be higher for some users than others), quantities of augmented streamflow may be less in below normal water years but the value of the water could be higher, etc. 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 will need to be made in this analysis:

- The estimates of increases in precipitation and the resultant estimates of increases in the annual average inflow 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.
- 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 and Estimated Benefit/Cost Ratio for the Combined Target Areas of Lopez and Salinas Reservoirs for a 9% Precipitation Increase

Seeding Mode	**Est. Increased Streamflow**	**Est. Cost**	**Cost/Ac. Ft.**	**Est. Benefit/Cost Ratio**
Four AHOGS Dispensers	10,563	$136,000	$12.88	93/1
Seeding Aircraft	10,563	$268,600	$25.43	47/1
Combined Ground and Aircraft	10,563	$312,700	$29.60	41/1

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 and Estimated Benefit/Cost Ratio for the Combined Target Areas of Lopez and Salinas Reservoirs for a 17% Precipitation Increase

Seeding Mode	**Est. Increased Streamflow**	**Est. Cost**	**Cost/Ac. Ft.**	**Est. Benefit/Cost Ratio**
Four AHOGS Dispensers	20,283	$136,000	$6.71	179/1
Seeding Aircraft	20,283	$268,600	$13.21	91/1
Combined Ground and Aircraft	20,283	$312,700	$15.41	78/1

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.

8.0 SUMMARY

North American Weather Consultants (NAWC) was contracted by the San Luis Obispo County Flood Control and Water Conservation District (District) to conduct a feasibility/design study for a winter cloud seeding program to target the Lopez Lake and Salinas Reservoir (LLSR) drainage basins located in southern San Luis Obispo County, California. A contract was developed between District and NAWC dated May 5, 2016. 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 Lopez Lake and Salinas Reservoir program. 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 strongly 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 on this study. Long-term precipitation gage 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 (Nov-Apr) Precipitation Increases

Stream gage site	Regression for Lopez Dam Inflow	Regression for Lopez Creek Gage
9% Precipitation increase	+17.8%	+13.4%
Inflow to Salinas Dam	+3100 AF	+2334 AF
Inflow to Lopez Dam	+2926 AF	+2203 AF
Total increase for +9% precipitation	6026 AF	+4537 AF
17% Precipitation increase	+33.7%	+26.3%
Inflow to Salinas Dam	+5855 AF	+4579 AF
Inflow to Lopez Dam	+5527 AF	+4322 AF
Total increase for +17% precipitation	11,382 AF	+8901 AF

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. For 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 operations and maintenance costs 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 8-2 Estimated Costs per Acre Foot and Estimated Benefit/Cost Ratio for the Combined Target Areas of Lopez and Salinas Reservoirs for a 9% Precipitation Increase

Seeding Mode	Est. Increased Streamfolw	Est. Cost	Cost/Ac. Ft.	Est. Benefit/Cost Ratio
Four AHOGS Dispensers	10,563	$136,000	$12.88	93/1
Seeding Aircraft	10,563	$268,600	$25.43	47/1
Combined Ground and Aircraft	10,563	$312,700	$29.60	41/1

Table 8-3 Estimated Costs per Acre Foot and Estimated Benefit/Cost Ratio for the Combined Target Areas of Lopez and Salinas Reservoirs for a 17% Precipitation Increase

Seeding Mode	Est. Increased Streamfolw	Est. Cost	Cost/Ac. Ft.	Est. Benefit/Cost Ratio
Four AHOGS Dispensers	20,283	$136,000	$6.71	179/1
Seeding Aircraft	20,283	$268,600	$13.21	91/1
Combined Ground and Aircraft	20,283	$312,700	$15.41	78/1

To place the results presented in Tables 8-2 and 8-3 in context, the estimated results in Table 8-2 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 8-3 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 (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 two 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 and 8-3 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.

As suggested earlier, these data indicate that the potential program would be considered strongly economically feasible which is driven by the estimated value of the water of $1200 per acre-foot. The ASCE publication 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 values in Tables 8-2 and 8-3 are an order of magnitude higher or greater 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 the estimated benefit/cost ratios would still be greater than 5/1. **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.**

There would be some upfront costs in establishing a winter cloud seeding program for the Lake Lopez and Salinas Reservoir watersheds. For example, should the ground-based seeding mode be implemented there would be tasks of 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 Nino in the tropical Pacific. During La Nina 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 freezng 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:
(700 millibars, or mb): Corresponds to approximately 10,000 feet above sea level (MSL); 850 mb corresponds to about 5,000 feet MSL; and 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.

Updaft: 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

CLIMATOLOGICAL PRECIPITATION DATA

Station	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Year
Lopez Rec Area	0.10	0.00	0.10	0.96	0.77	3.14	3.72	2.47	2.62	1.32	0.36	0.15	15.70
Hog Canyon	0.03	0.03	0.03	0.46	0.55	2.22	2.42	1.60	1.57	0.68	0.18	0.06	9.82
Atascadero	0.05	0.01	0.00	0.83	1.05	2.40	2.32	2.30	1.62	0.88	0.16	0.05	11.78
Camp San Luis	0.14	0.01	0.01	1.33	1.17	3.40	3.59	2.76	2.41	1.18	0.32	0.15	16.46
Santa Rosa @ Main	0.09	0.02	0.03	1.13	1.12	3.62	3.02	3.45	2.37	1.06	0.39	0.15	16.54
Salinas Dam	0.09	0.01	0.07	1.13	0.88	3.00	2.92	2.33	2.23	1.20	0.23	0.06	14.16
Santa Margarita	0.09	0.01	0.05	1.05	0.96	3.72	3.85	2.74	1.73	1.17	0.19	0.04	15.59
Los Osos Landfill	0.18	0.03	0.08	1.01	0.81	2.96	3.46	2.60	2.22	0.98	0.34	0.14	14.81
Nipomo East	0.10	0.01	0.02	0.87	0.86	3.46	2.92	2.18	2.14	1.18	0.24	0.08	14.07
Nipomo South	0.04	0.00	0.06	0.83	0.89	3.08	2.46	1.83	1.79	1.12	0.21	0.29	12.60
Lopez Dam	0.17	0.01	0.03	1.31	1.34	4.71	3.95	3.15	2.49	0.97	0.28	0.20	18.37
Davis Peak	0.17	0.03	0.01	0.99	1.62	3.89	3.03	2.15	2.47	1.26	0.42	0.20	16.24
Arroyo Grande	0.18	0.20	0.04	0.83	0.98	3.13	2.56	2.10	1.63	0.75	0.16	0.16	13.33
Canet	0.32	0.02	0.12	1.30	0.89	3.63	3.77	2.66	2.19	0.76	0.12	0.16	15.60
SLO Reservoir	0.15	0.02	0.01	1.29	1.03	4.51	4.38	3.09	2.71	1.51	0.38	0.16	19.25
South Portal	0.13	0.05	0.03	1.30	1.65	5.16	4.27	3.81	3.20	1.71	0.41	0.21	21.94
Oceano	0.07	0.00	0.15	0.70	1.16	2.49	2.16	2.22	1.52	0.83	0.30	0.10	11.75
Gas Company	0.13	0.01	0.02	0.63	1.05	3.59	3.41	2.60	2.28	1.40	0.31	0.12	15.55
AG Corp Yard	0.05	0.00	0.11	0.67	1.59	2.65	3.27	3.28	2.41	1.01	0.29	0.05	15.38
Atascadero MW Co.	0.02	0.03	0.18	0.66	1.60	3.14	3.71	3.66	2.85	1.24	0.33	0.05	17.45
Avila Beach	0.00	0.01	0.14	0.81	1.94	4.30	3.56	3.21	2.60	1.20	0.47	0.08	18.33
Bates	0.02	0.03	0.21	0.74	1.65	2.61	3.14	3.20	2.64	1.24	0.33	0.06	15.87
Cal Poly	0.02	0.04	0.24	0.89	2.00	3.92	4.69	4.37	3.49	1.56	0.47	0.10	21.78
CDF Nipomo	0.02	0.04	0.19	0.73	1.52	2.51	3.12	3.21	2.67	1.10	0.23	0.05	15.37
Comm Shop (SLO)	0.09	0.01	0.04	1.14	1.97	3.72	4.43	4.33	2.52	1.42	0.48	0.12	20.26
Lopez Lake	0.07	0.03	0.21	1.21	2.17	3.87	4.38	4.70	3.64	1.45	0.57	0.12	22.41
Mehlschau	0.03	0.04	0.16	0.71	1.73	2.87	3.21	3.19	2.71	1.37	0.36	0.08	16.46
Parkhill CDF	0.00	0.00	0.15	1.04	1.37	3.81	4.32	4.75	2.78	1.08	0.43	0.10	19.83
Perozzi Ranch	0.04	0.06	0.27	0.92	2.23	3.52	4.47	4.26	3.55	1.57	0.37	0.08	21.34
Santa Margarita UOC	0.02	0.03	0.20	0.72	2.25	3.78	4.70	4.45	3.78	1.44	0.32	0.03	21.71
KSBP Airport	0.02	0.03	0.26	0.95	1.94	3.89	4	4.41	3.45	1.29	0.4	0.07	20.7
Santa Margarita BS	0.03	0.05	0.31	1.39	3.34	5.4	6.71	6.42	4.59	2.23	0.57	0.09	31.14
Average	**0.08**	**0.03**	**0.11**	**0.95**	**1.44**	**3.50**	**3.62**	**3.23**	**2.59**	**1.22**	**0.33**	**0.11**	**17.24**
% of Annual Rainfall	**0.48**	**0.16**	**0.64**	**5.53**	**8.35**	**20.32**	**21.02**	**18.76**	**15.02**	**7.10**	**1.93**	**0.65**	

APPENDIX B

HYSPLIT MODEL RUNS

The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model is the newest version of a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations. As a result of a joint effort between NOAA and Australia's Bureau of Meteorology, the model has recently been upgraded. New features include improved advection algorithms, updated stability and dispersion equations, a new graphical user interface, and the option to include modules for chemical transformations. Without the additional dispersion modules, HYSPLIT computes the advection of a single pollutant particle, or simply its trajectory.

The dispersion of particles released into the atmosphere is calculated by assuming either puff or particle dispersion. In the puff model, puffs expand until they exceed the size of the meteorological grid cell (either horizontally or vertically) and then split into several new puffs, each with its share of the pollutant mass. In the HYSPLIT particle model, a fixed number of initial particles are advected about the model domain by the mean wind field and a turbulent component. The model's default configuration assumes a puff distribution in the horizontal and particle dispersion in the vertical direction. In this way, the greater accuracy of the vertical dispersion parameterization of the particle model is combined with the advantage of having an ever-expanding number of particles represent the pollutant distribution.

The model can be run interactively on the Web through the READY system on the NOAA site, or the code executable and meteorological data can be downloaded to a Windows PC. The Web version has been configured with some limitations to avoid computational saturation of the web server. The registered PC version is complete with no computational restrictions, except that the user must download the necessary meteorological data files. The unregistered version is identical to the registered version except that it will not work with forecast meteorology data files.

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 real-time predictions of plume transport that were used previously utilized input fields from the NAM model at a 12 km grid spacing. Data are now available for real-time simulations that have a grid resolution of 4 km (similar to some of the WRF models). The 3 km data are not archived due to the size of the files, thus providing only simulations in real-time. Simulations for prior storm events may be run using NAM 12 km archived data. The accuracy of the plume predictions is sensitive to the grid size, especially in areas that have underlying complex terrain (e.g. mountainous areas). The smaller the grid spacing becomes the better the predictions in these situations.

The depictions from HYSPLIT are of the transport of the seeding plumes. The seeding material needs to interact with the convective bands forming ice crystals which grow into snowflakes which then fall to the ground changing into rain drops as they pass through the freezing level. These processes occur as the band moves downwind in time. Consequently, these depictions are of the initial transport and diffusion phase of the plumes while the resultant fallout of augmented precipitation would occur downwind of these plume depictions (typically to the east or northeast of these plume depictions). Although the plumes predicted by HYSPLIT may pass over urbanized areas (e.g., San Luis Obispo), there would be no or minimal impact in these areas since the upper portions of the plume are just reaching activation levels near the tail end of these predicted plume locations. 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. This model may be available to the public sometime in the future.

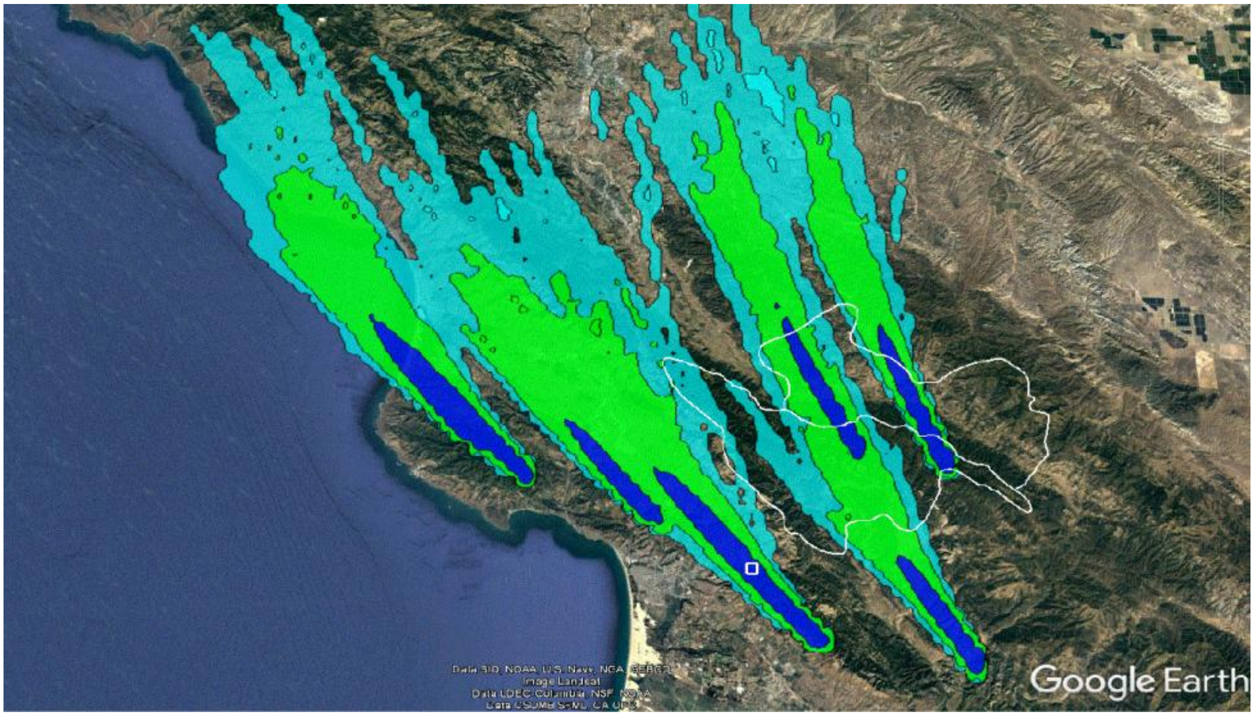

Figure B-1 One-hour HYSPLIT run for December 5, 2010 during the passage of a convective band with an approaching upper level trough.

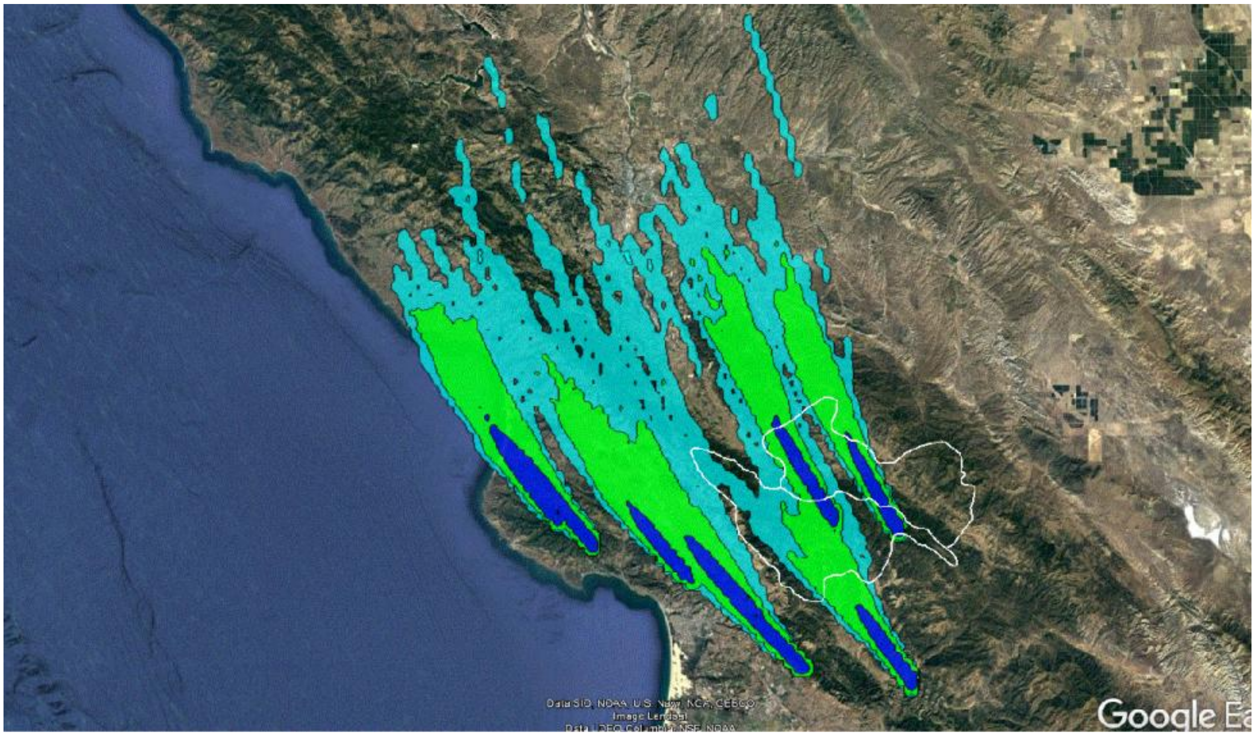

Figure B-2 One-hour HYSPLIT run for January 2, 2011 associated with an upper low.

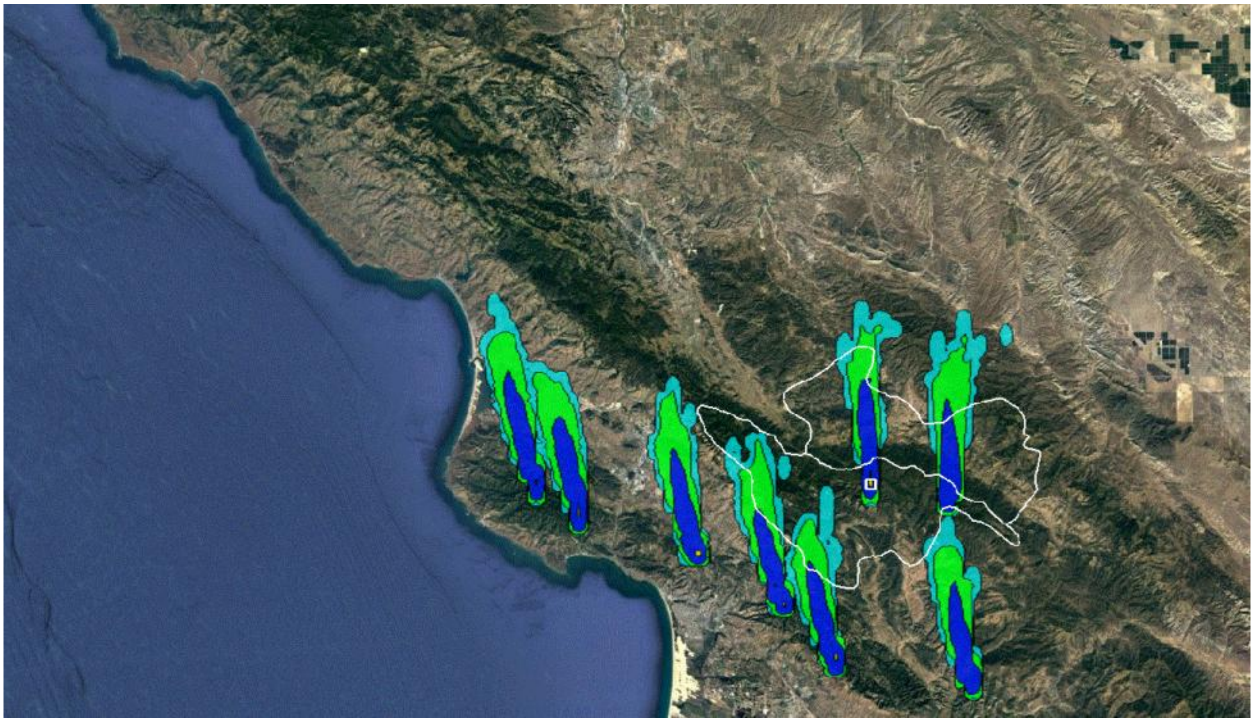

Figure B-3 One-hour HYSPLIT run for February 19, 2011 associated with a cold upper low.

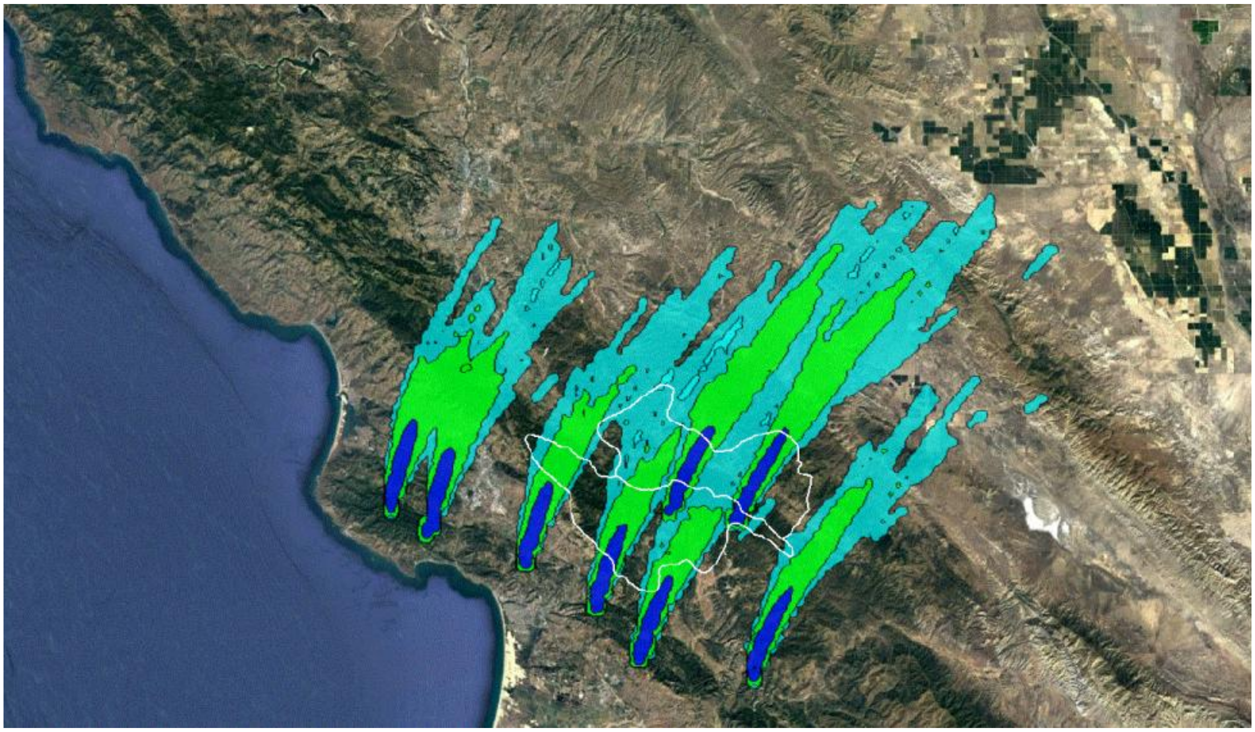

Figure B-4 One-hour HYSPLIT run for January 21, 2012 associated with a warm, weak upper level trough.

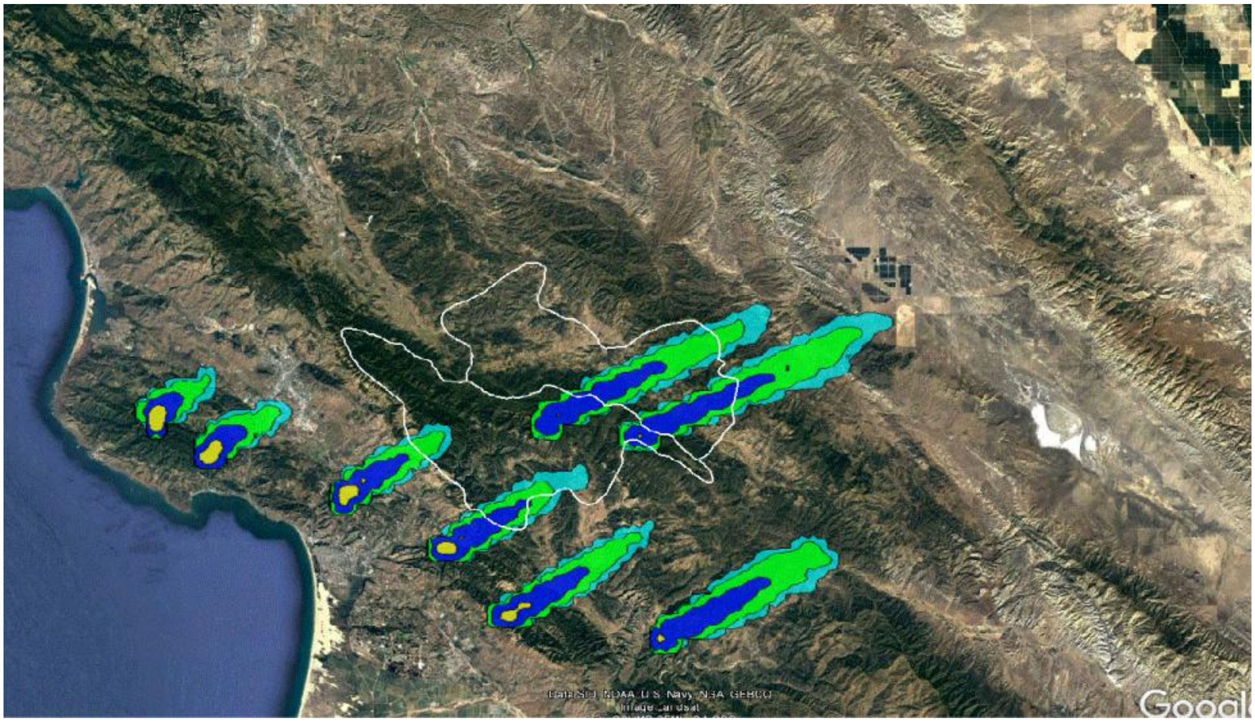

Figure B-5 One-hour HYSPLIT run for April 10, 2012 associated with a deep upper level trough.

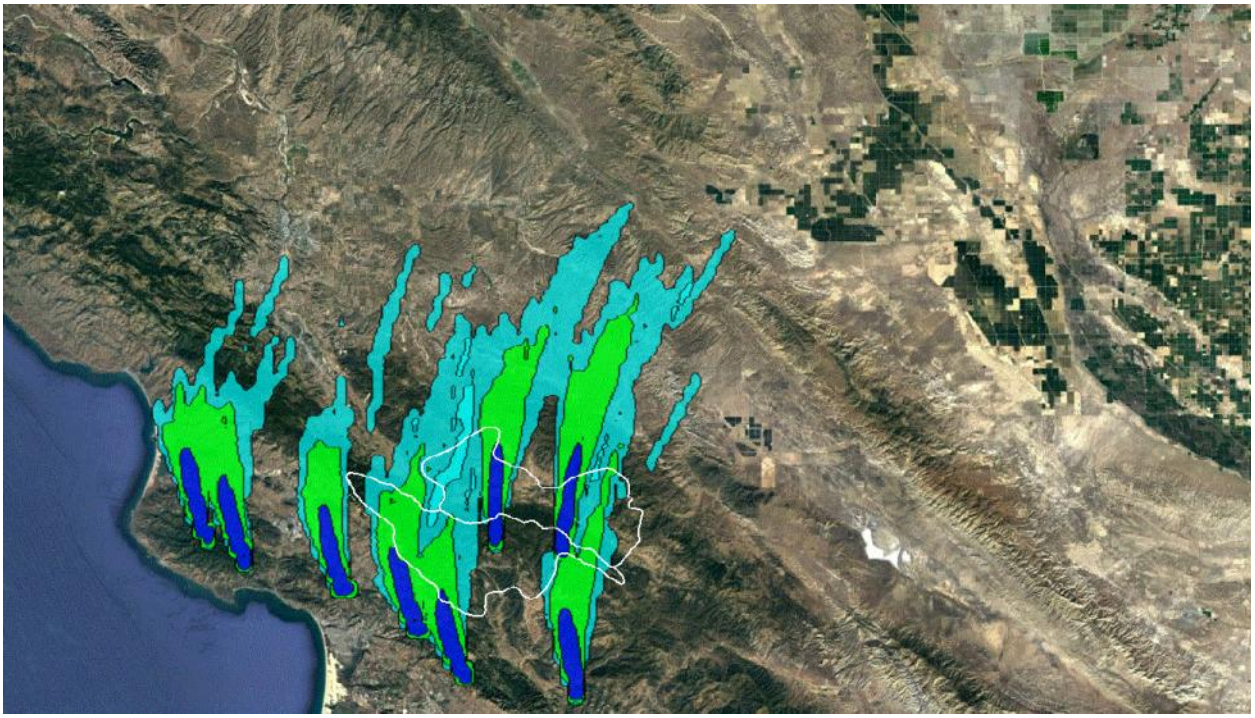

Figure B-6 One-hour HYSPLIT run for December 12, 2014 associated with an upper level trough.

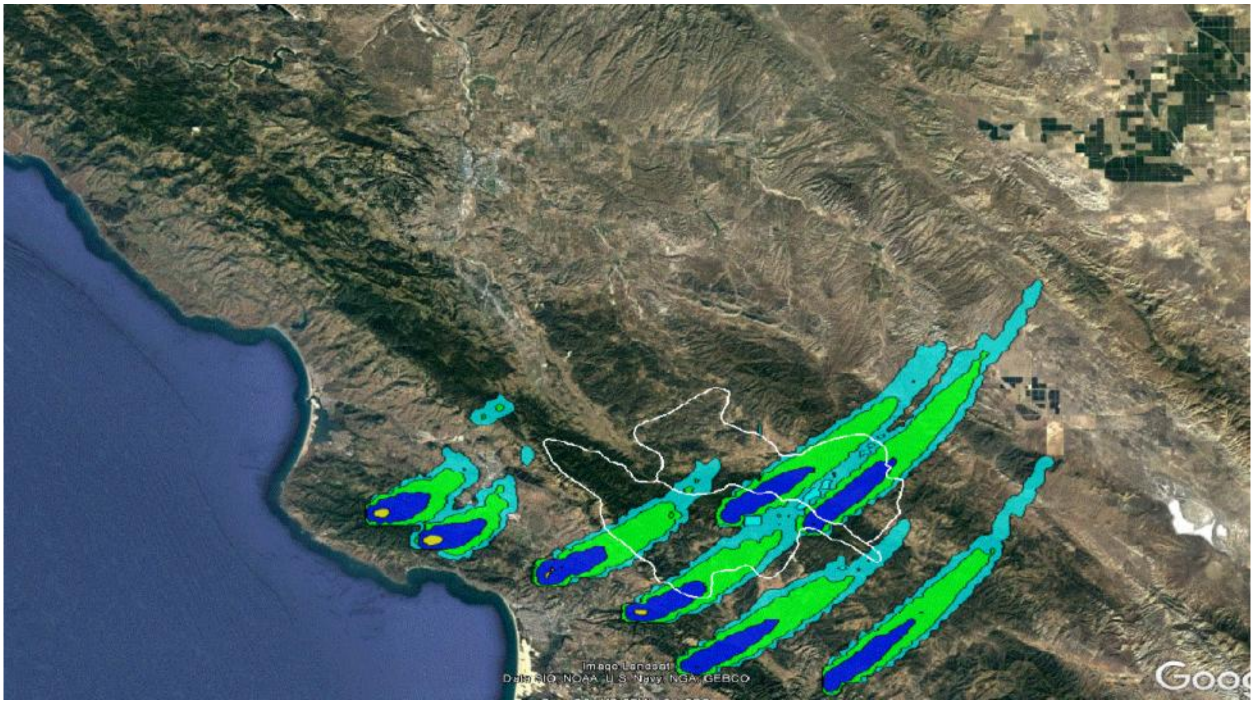

Figure B-7 One-hour HYSPLIT run for December 12, 2014 associated with an upper level trough.

APPENDIX C

DATA SETS USED IN THE REGRESSION EQUATIONS

Precipitation Gauges:

Salinas Dam Monthly Precipitation (inches)   Red values = estimates

Water Yr	Nov	Dec	Jan	Feb	Mar	Apr	Nov-Apr
1968	3.14	1.80	1.65	1.02	3.20	1.25	12.06
1969	1.55	2.73	22.87	17.29	1.10	3.04	48.58
1970	1.01	0.65	5.27	1.57	3.98	0.01	12.49
1971	5.70	7.22	1.86	0.20	1.23	1.17	17.38
1972	1.68	8.32	1.56	0.63	0.00	0.65	12.84
1973	6.99	1.72	8.95	11.01	4.14	0.00	32.81
1974	4.44	3.90	7.70	0.16	7.14	1.21	24.55
1975	0.52	4.74	0.24	7.71	5.63	3.02	21.86
1976	0.03	0.10	0.09	3.64	2.25	0.98	7.09
1977	0.66	1.75	1.83	0.13	1.62	0.00	5.99
1978	0.09	7.20	9.46	9.02	9.80	4.59	40.16
1979	2.42	0.00	4.98	4.79	5.00	0.04	17.23
1980	1.15	3.08	6.69	11.33	4.12	0.88	27.25
1981	0.00	1.86	6.19	1.40	8.28	0.80	18.53
1982	2.22	1.48	5.12	1.26	7.30	6.06	23.44
1983	7.75	6.35	10.75	8.06	9.72	4.72	47.35
1984	4.46	7.20	0.22	0.63	0.83	0.70	14.04
1985	3.56	3.70	0.70	2.13	3.23	0.11	13.43
1986	5.00	1.12	2.47	10.07	7.62	0.30	26.58
1987	0.38	0.82	2.17	2.16	3.97	0.11	9.61
1988	2.04	4.15	2.85	2.01	1.85	2.81	15.71
1989	1.61	5.28	0.77	1.98	1.81	0.98	12.43
1990	0.90	0.00	2.62	3.44	0.59	0.37	7.92
1991	0.21	0.29	0.68	2.57	14.17	0.18	18.10
1992	0.35	5.94	2.39	10.38	2.77	0.03	21.86
1993	0.00	6.71	12.27	8.07	3.73	0.14	30.92
1994	0.85	1.87	2.09	6.32	1.74	1.08	13.95
1995	2.24	0.97	17.50	1.86	14.16	0.23	36.96
1996	0.18	2.87	3.65	9.54	2.99	1.14	20.37
1997	2.71	9.39	12.70	0.00	0.00	0.00	24.80
1998	4.65	4.22	4.75	17.02	3.50	3.18	37.32
1999	1.55	1.22	3.32	1.94	3.68	2.43	14.14
2000	1.15	0.08	3.91	11.37	1.64	2.84	20.99
2001	0.03	0.00	7.30	7.50	5.79	3.06	23.68
2002	4.80	3.41	0.97	0.85	1.78	0.61	12.42
2003	5.10	7.05	0.10	2.49	3.07	1.70	19.51
2004	2.07	2.95	0.94	6.21	0.66	0.00	12.83

Water Yr	Nov	Dec	Jan	Feb	Mar	Apr	Nov-Apr
2005	1.62	10.32	9.49	5.83	3.74	1.58	32.58
2006	0.43	1.91	8.67	2.69	5.91	6.97	26.58
2007	0.13	2.24	1.27	3.94	0.25	0.55	8.38
2008	0.09	4.19	12.90	3.37	0.07	0.27	20.89
2009	1.35	2.43	0.66	5.03	2.48	0.86	12.81
2010	0.02	5.34	9.95	5.23	0.93	3.83	25.30
2011	2.22	12.31	2.30	5.16	8.39	0.18	30.56
2012	3.02	0.18	2.84	0.28	3.38	3.38	13.08
2013	0.00	5.55	0.60	0.53	0.86	0.03	7.57
2014	0.10	0.28	0.02	3.84	3.47	1.60	9.31
2015	1.30	5.02	0.22	2.91	0.11	0.78	10.34
2016	1.51	1.64	6.72	1.11	5.05	0.20	16.23

San Luis Obispo Polytech (inches) Red = estimated data; Blue = missing some days in record but original total was used

Water Yr	Nov	Dec	Jan	Feb	Mar	Apr	Nov-Apr
1968	3.83	3.05	2.43	2.07	3.70	1.31	16.39
1969	2.10	3.92	24.63	15.16	1.88	3.72	51.41
1970	0.89	1.73	7.28	1.42	4.11	0.18	15.61
1971	6.02	8.51	1.89	0.42	0.73	1.56	19.13
1972	2.00	7.03	1.03	0.86	0.00	0.89	11.81
1973	6.79	2.00	13.83	9.67	4.94	0.00	37.23
1974	3.55	4.90	8.17	0.32	8.97	2.81	28.72
1975	0.75	4.93	0.26	8.35	5.90	2.00	22.19
1976	0.36	0.18	0.01	4.17	2.54	0.88	8.14
1977	1.03	2.49	2.01	0.08	2.13	0.06	7.80
1978	0.00	8.49	15.76	10.71	8.09	4.37	47.42
1979	2.43	2.24	4.62	5.99	4.03	0.24	19.55
1980	1.21	4.84	9.52	11.91	2.60	0.70	30.78
1981	0.01	2.10	6.40	2.15	7.48	0.34	18.48
1982	2.97	2.04	5.87	1.65	8.89	4.12	25.54
1983	6.28	4.97	10.05	10.53	8.61	3.30	43.74
1984	6.54	6.72	0.18	0.97	1.02	0.82	16.25
1985	3.61	3.76	0.72	1.49	3.07	0.30	12.95
1986	4.39	2.03	2.65	11.79	7.26	0.16	28.28
1987	0.28	1.51	2.48	2.75	2.43	0.40	9.85
1988	1.49	4.95	2.87	2.67	1.29	3.35	16.62
1989	1.85	8.08	0.98	1.62	2.30	0.67	15.50

Water Yr	Nov	Dec	Jan	Feb	Mar	Apr	Nov-Apr
1990	0.55	0.00	4.40	2.98	0.70	0.48	9.11
1991	0.36	0.43	0.81	2.34	12.82	0.43	17.19
1992	0.58	4.49	3.43	9.84	3.15	0.10	21.59
1993	0.00	5.45	10.51	8.61	4.03	0.25	28.85
1994	1.89	2.20	2.93	5.97	1.43	1.46	15.88
1995	2.51	1.15	16.09	2.25	16.48	1.12	39.60
1996	0.40	3.57	4.33	10.98	1.78	1.92	22.98
1997	4.43	10.88	13.31	0.46	0.00	0.05	29.13
1998	5.84	5.32	6.86	15.07	3.79	3.58	40.46
1999	1.88	1.22	3.62	2.37	5.19	2.07	16.35
2000	1.69	0.08	4.33	13.17	1.92	2.97	24.16
2001	0.03	0.19	8.10	7.17	4.94	1.87	22.30
2002	5.47	4.18	1.31	0.84	2.14	1.33	15.27
2003	4.42	8.07	0.38	3.16	2.38	1.93	20.34
2004	2.71	3.25	1.13	8.29	0.61	0.00	15.99
2005	2.26	8.25	9.45	6.64	4.75	0.91	32.26
2006	0.70	0.83	2.38	0.64	4.59	1.29	10.43
2007	0.01	2.08	1.39	3.39	0.44	0.60	7.91
2008	0.06	2.20	12.92	2.75	0.14	0.29	18.36
2009	1.51	1.90	0.91	5.86	1.35	0.49	12.02
2010	0.12	3.40	6.15	4.46	1.40	2.42	17.95
2011	1.85	9.67	2.26	0.96	0.17	0.01	14.92
2012	3.2	0.26	3.27	0.73	2.95	3.69	14.10
2013	3.07	6.42	1.35	0.89	0.90	0.00	12.63
2014	0.34	0.27	0.03	5.83	2.57	1.08	10.12
2015	1.51	5.89	0.12	2.31	0.02	1.49	11.34
2016	1.78	2.50	6.85	0.70	5.84	0.25	17.92

Atascadero Mutual Water

Water Yr	Nov	Dec	Jan	Feb	Mar	Apr	Nov-Apr
1968	2.09	2.50	1.83	0.99	2.35	1.17	10.93
1969	1.12	3.34	16.62	12.16	0.76	1.63	35.63
1970	0.46	0.82	5.97	1.11	4.07	0.11	12.54
1971	4.49	6.69	1.63	0.22	1.10	0.94	15.07
1972	0.81	4.46	0.80	0.30	0.00	0.44	6.81
1973	4.21	1.35	6.20	7.17	2.45	0.00	21.38
1974	3.75	2.34	6.20	1.75	3.61	1.25	18.90
1975	0.47	3.19	0.09	5.00	4.38	1.58	14.71

Water Yr	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**Nov-Apr**
1976	0.00	0.10	0.00	2.87	1.59	0.85	5.41
1977	1.56	1.87	1.71	0.16	1.37	0.00	6.67
1978	0.33	7.57	7.92	7.79	6.78	3.21	33.60
1979	2.08	1.22	4.48	4.73	3.91	0.11	16.53
1980	0.89	3.36	6.41	11.55	3.05	1.00	26.26
1981	0.01	0.74	4.07	1.57	6.64	0.93	13.96
1982	1.21	1.44	4.15	1.15	5.93	4.91	18.79
1983	5.13	3.79	9.21	5.72	8.70	3.11	35.66
1984	3.61	5.26	0.20	0.36	0.98	0.69	11.10
1985	3.58	3.03	0.85	1.69	2.77	0.15	12.07
1986	3.37	1.12	2.13	10.07	6.59	0.00	23.28
1987	0.24	0.95	1.80	2.44	3.10	0.00	8.53
1988	2.71	3.67	3.01	2.60	1.50	2.20	15.69
1989	1.13	5.22	1.57	0.87	1.26	0.49	10.54
1990	0.50	0.00	3.49	2.85	0.45	0.26	7.55
1991	0.25	0.40	0.97	4.09	11.10	0.20	17.01
1992	0.25	4.30	1.98	10.47	2.75	0.00	19.75
1993	0.00	4.96	9.51	7.65	3.39	0.15	25.66
1994	0.81	2.07	2.09	1.99	0.65	0.20	7.81
1995	0.60	0.10	13.98	0.25	13.10	0.07	28.10
1996	0.20	2.67	3.40	9.32	2.70	0.75	19.04
1997	2.78	7.67	9.60	0.10	0.00	0.00	20.15
1998	3.99	4.27	5.50	11.49	2.25	2.82	30.32
1999	1.29	0.88	3.07	2.02	3.25	1.25	11.76
2000	0.72	0.10	3.91	7.99	1.73	2.03	16.48
2001	0.10	0.30	5.03	5.60	4.15	1.55	16.73
2002	2.70	2.42	0.40	0.30	1.27	0.33	7.42
2003	1.88	4.38	0.13	1.30	1.10	1.00	9.79
2004	0.58	1.84	1.00	4.97	0.37	0.00	8.76
2005	2.32	9.38	6.07	5.71	3.12	1.09	27.69
2006	0.35	1.78	8.21	1.64	5.39	3.76	21.13
2007	0.36	1.97	0.91	3.14	0.26	0.60	7.24
2008	0.03	3.21	9.20	2.68	0.01	0.26	15.39
2009	1.41	1.72	0.85	4.15	1.84	0.60	10.57
2010	0.08	4.71	8.34	3.70	0.70	3.00	20.53
2011	2.28	8.86	2.65	3.63	5.75	0.08	23.25
2012	2.14	0.16	3.09	0.27	2.20	2.60	10.46
2013	1.25	4.24	1.12	0.49	0.47	0.00	7.57
2014	0.15	0.54	0.00	3.48	3.14	1.55	8.86
2015	1.12	4.93	0.57	3.04	0.21	0.67	10.54
2016	1.41	1.34	5.40	1.31	4.30	0.24	14.00

Mehlschau #38

Water Yr	Nov	Dec	Jan	Feb	Mar	Apr	Nov-Apr
1968	2.86	1.84	1.12	1.32	2.71	0.84	10.69
1969	1.38	2.53	11.21	7.68	1.59	2.05	26.44
1970	0.92	1.13	3.94	1.54	3.50	0.06	11.09
1971	4.41	5.06	1.78	0.17	0.64	1.17	13.23
1972	1.55	3.86	0.31	0.47	0.00	0.60	6.79
1973	4.68	2.43	6.46	6.21	4.50	0.03	24.31
1974	3.76	3.49	6.31	0.16	6.35	1.79	21.86
1975	0.45	5.12	0.16	4.57	3.01	1.14	14.45
1976	0.21	0.19	0.00	3.69	2.49	0.69	7.27
1977	0.91	1.80	1.36	0.08	1.68	0.02	5.85
1978	0.28	6.19	6.88	7.90	5.29	3.85	30.39
1979	1.66	1.25	4.44	4.86	4.27	0.33	16.81
1980	0.69	2.18	6.18	5.51	2.40	0.89	17.85
1981	0.00	1.83	4.09	2.53	6.67	0.57	15.69
1982	2.71	1.92	3.56	1.37	5.14	4.08	18.78
1983	4.12	2.72	7.19	10.06	8.51	2.80	35.40
1984	3.80	3.89	0.09	0.55	0.86	0.57	9.76
1985	3.19	2.87	1.03	2.04	1.96	0.35	11.44
1986	3.90	1.05	1.31	5.29	5.73	0.61	17.89
1987	0.23	1.89	2.35	2.53	4.66	0.44	12.10
1988	1.22	3.59	2.17	2.06	0.58	3.29	12.91
1989	1.79	6.28	0.67	1.05	1.64	0.35	11.78
1990	0.42	0.06	2.11	1.86	0.48	0.40	5.33
1991	0.32	0.58	1.14	1.81	12.04	0.33	16.22
1992	0.45	3.88	2.12	8.02	2.17	0.03	16.67
1993	0.00	3.81	6.02	5.40	4.95	0.18	20.36
1994	1.56	1.67	2.67	3.48	1.76	1.10	12.24
1995	1.95	1.25	12.57	2.00	10.02	0.77	28.56
1996	0.58	2.37	3.65	8.54	1.68	1.03	17.85
1997	4.89	8.08	7.65	0.11	0.00	0.00	20.73
1998	5.42	3.39	5.42	13.67	4.09	3.68	35.67
1999	2.44	1.04	2.95	1.65	4.85	2.26	15.19
2000	1.73	0.04	2.55	10.04	1.81	3.34	19.51
2001	0.00	0.11	5.75	5.80	4.94	1.85	18.45
2002	3.77	2.37	1.47	0.41	1.15	0.37	9.54
2003	3.94	5.25	0.12	2.62	2.25	1.48	15.66
2004	2.98	3.05	1.10	5.31	0.91	0.00	13.35
2005	0.83	5.07	6.64	3.34	4.38	0.76	21.02
2006	1.16	1.71	8.54	1.37	5.41	5.95	24.14
2007	0.38	2.59	1.09	2.60	0.36	0.87	7.89
2008	0.12	2.98	8.78	3.00	0.05	0.26	15.19

Water Yr	Nov	Dec	Jan	Feb	Mar	Apr	Nov-Apr
2009	2.27	3.24	0.36	4.27	1.00	0.45	11.59
2010	0.02	3.71	6.78	4.22	1.58	2.95	19.26
2011	1.94	12.42	0.99	3.31	5.88	0.22	24.76
2012	2.26	0.18	2.47	0.40	2.77	2.70	10.78
2013	0.89	4.72	0.91	0.55	0.78	0.11	7.96
2014	0.22	0.35	0.01	2.47	2.79	1.05	6.89
2015	1.72	4.49	0.14	0.96	0.39	0.66	8.36
2016	1.20	2.26	3.84	0.58	3.47	0.50	11.85

Streamflow Data

Lopez Creek near Arroyo Grande

Water Yr	Annual (Jul – Jun) Acre-Feet
1969	23323
1970	5509
1971	3992
1972	1946
1973	11559
1974	8663
1975	4804
1976	1901
1977	1480
1978	14180
1979	4729
1980	11918
1981	6651
1982	8066
1983	24975
1984	7684
1985	3747
1986	9638
1987	3504
1988	2907
1989	2450
1990	1509
1991	2689
1992	3478

Water Yr	**Annual (Jul – Jun) Acre-Feet**
1993	7954
1994	2804
1995	13111
1996	7978
1997	16021
1998	24411
1999	6700
2000	6741
2001	6365
2002	2698
2003	3321
2004	4120
2005	10787
2006	8002
2007	2541
2008	4457
2009	1681
2010	5536
2011	9684
2012	2877
2013	1997
2014	1159
2015	1004

Lopez Dam calculated inflow

Water Yr	**Annual (Jul – Jun) Acre-Feet**
1969	56439
1970	9927
1971	7625
1972	3707
1973	17516
1974	17257
1975	8575
1976	3327
1977	2782
1978	35126
1979	8565
1980	31042

Water Yr	Annual (Jul – Jun) Acre-Feet
1981	8632
1982	14307
1983	89132
1984	16567
1985	6105
1986	20555
1987	5719
1988	4019
1989	3765
1990	3120
1991	6120
1992	6660
1993	16816
1994	4525
1995	32794
1996	16298
1997	43550
1998	59840
1999	12896
2000	**NA**
2001	13661
2002	4828
2003	5692
2004	6808
2005	21191
2006	16296
2007	4546
2008	7634
2009	2957
2010	**NA**
2011	**NA**
2012	**NA**
2013	**NA**
2014	**NA**
2015	**NA**

Salinas Dam calculated inflow

Water Yr	Annual (Jul – Jun) Acre-Feet
1988	2650
1989	2416
1990	801
1991	7057
1992	2702
1993	45245
1994	3052
1995	72186
1996	17944
1997	43142
1998	71833
1999	5983
2000	13305
2001	18125
2002	2439
2003	4956
2004	1556
2005	62826
2006	45651
2007	1904
2008	15710
2009	1767
2010	7873
2011	46568
2012	2410
2013	1867
2014	1257
2015	635
2016	712