Santa Ana River Watershed

Weather Modification and Feasibility Study

Final Report

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TABLE OF CONTENTS

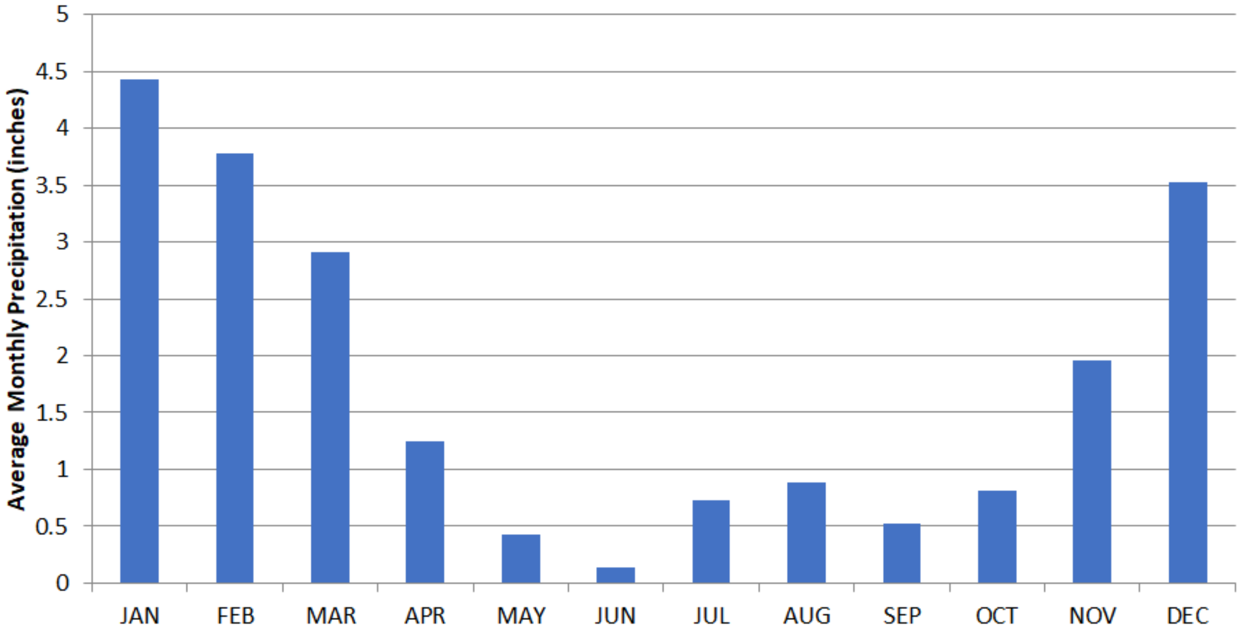
EXECUTIVE SUMMARY

General Climatology

The Santa Ana River watershed shares a Mediterranean-type climate with the rest of Southern California. Typical for this climate, the watershed experiences warm, dry summers and cool, somewhat moist winters. Though precipitation can be highly variable season to season, after reviewing over 30 years of seasonal precipitation there are significant patterns that emerge.

There is a strong correlation between elevation and average precipitation. Mountainous areas (above 2,000-3,000 feet) experience 20-40 inches of precipitation per year. Lower elevation coastal areas receive between about 10-20 inches precipitation annually. Semi-arid regions generally receive less than 10 inches of precipitation annually.

Average precipitation exhibits a strong seasonal trend. This is illustrated in the figure below. The greatest precipitation generally occurs between the months of December – March. On average, the months of January through March experience the most snowfall. Based on seasonality of precipitation and storm activity in this region, the meteorological analysis for this study focused on the November - April season.



Monthly precipitation averages at Big Bear Lake, 1961-2019. This illustrates the seasonal patterns typical of the mountainous areas of southern California.

Average snowfall varies dramatically with elevation, with most snowfall occurring over 5,000 feet and areas above 7,000 feet observing 100-150 inches annually. Snowfall becomes more sporadic below about 4,000 feet.

Project Design

The Santa Ana River Watershed has four potential target areas for weather modification (or more colloquially referred to as “cloud seeding”). Each of the target areas exhibit relatively distinct geographical and climatological attributes. Listed in order of their contribution to seasonal runoff (least to greatest):

- The northwest target area (NW Target), bordering Los Angeles and San Bernardino Counties encompasses a portion of the Central Transverse Ranges, to the west of the I-15 freeway. Estimated average seasonal runoff: 25,000 AF.
- The northeast target area (NE Target) in San Bernardino County encompasses the area of the Central Transverse Ranges east of I-15, extending down to I-10 north of Palm Springs. Estimated average seasonal runoff: 65,000 AF
- The southeast target area (SE Target) includes the mountains in Riverside County centered just to the west and southwest of Palm Springs. Estimated average seasonal runoff: 10,000 AF.
- The southwest target area (SW Target) area includes the mountain range that lies on the border of Orange and Riverside counties. Estimated average seasonal runoff: 5,000 AF.

Storm events that affected southwestern California over five winter seasons were analyzed and a detailed climatology was developed. From this, an array of seeding sites for the Santa Ana Watershed’s four target areas was compiled. Sites were selected based on their common upwind location from their intended target areas, with the vast majority of sites located to the south through west of their target areas.

Two methods of ground-based seeding were considered. The first method incorporates manually operated ground based CNGs (Cloud Nuclei Generators), which burn a solution of AgI and acetone. These generators create a continuous plume of seeding material that provides broad coverage over primarily mountainous terrain with strong orographic effects. The second method of seeding from the ground incorporates NAWC proprietary AHOGS or (Automated High Output Ground Seeding) systems. These remotely operated units use burn in place flares that release a high concentration of silver iodide very rapidly. These generators are ideal for seeding convective bands with high concentrations of supercooled liquid water and strong vertical updrafts.

In addition to ground-based seeding, aerial seeding was also assessed. The use of a plane allows for the immediate release of seeding agents at the most desirable location within a cloud. Though highly effective, aerial seeding can be cost prohibitive and requires special permits and approvals from the Federal Aviation Administration (FAA).

For each of the four target areas NAWC considered their unique geographies and topographies, as well as their average contribution to runoff to determine the most advantageous seeding method or methods.

After determining the best general design for each target area, advanced computer modeling was utilized for a subset of the analyzed storm events in order to model the horizontal and vertical movement of seeding plumes from ground-based equipment and aerial release. Adaptations to equipment placement and flight tracks were made until results indicated successful dispersion of seeding agents over the designated targets for a variety of storm conditions.

Estimated Increases

To estimate the net potential gain in runoff for the Santa Ana watershed, NAWC first analyzed individual storm periods from five representative November - April seasons to determine the potential gain in precipitation from a well-executed weather modification program.

For the 58 storms that were reviewed over these five seasons, 81% had characteristics favorable for cloud seeding. Of the storms with favorable characteristics, 79% (64% of all storms) were considered to be seedable from ground-based sites, with the remaining 21% (17% of all storms) likely only seedable from aircraft. To determine the potential increases in precipitation, hourly rain gauge data was collected for each storm, and numerous storm attributes were carefully tabulated and considered.

Estimated seasonal increases to precipitation were determined for each target area by adding the potential increase for each individual storm event. The results for each target area over five seasons were then averaged to determine an average projected increase. The results are summarized in the tables below.

Following the determination of projected increases in precipitation, NAWC created regressions to model the relationship between precipitation and streamflow for each target area. Data were collected from rain gauges and streamflow gauges dating back, in some cases, to the 1920's. These models allowed NAWC to predict the impact that the aforementioned increases in precipitation would have on total seasonal runoff.

In most cases the correlation between precipitation and runoff was found to be very strong, with R-values near to or greater than 0.8. The following table summarizes both the precipitation increases estimates, and the resulting streamflow increase estimates, for a typical or "average" season. These estimates were used in the determination of the total potential benefit of a seeding program as described in this study.

Estimated precipitation and streamflow increases

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

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

Estimated Costs

Ground seeding in all four target areas with aerial seeding in the Northeast target area

	Rate	Frequency	
Annual Operations			
Set Up	$ 40,000	1	$ 40,000
Take Down	$ 31,000	1	$ 31,000
Reporting	$ 10,000	1	$ 10,000
Monthly Operations			
Fixed Services	$ 55,000	5	$ 275,000
Variable Items (timed expenses are billed on a per hour basis)			
Ground Flares	$ 110	60	$ 6,600
Generator Run Time	$ 19.50	600	$ 11,700
Flight Time	$ 375	30	$ 11,250
Aerial Flares	$ 110	150	$ 16,500
		TOTAL	**$ 402,050**
		COST PER ACRE-FOOT	**$ 35.61**
		Benefit to Cost	**7.16**

In order to calculate the benefit to cost ratio for this proposed program, SAWPA provided NAWC several estimates for untreated and unpressurized imported water resulting in an average calculated watershed wide value of $255 per acre-foot.

As seen in the table of estimated costs, the cost of a combined ground and aerial program will be roughly $400,000, yielding a benefit to cost ratio of roughly 7:1. NAWC estimates the cost of a ground-only program to be roughly $208,000, with a projected benefit to cost ratio of roughly 10:1. The ground only program has therefore been deemed more efficient than the combined ground and aerial program. Our recommendation would thus, be to start with a ground only program and expand into a ground and aerial program as needs for additional water increase in the future.

Conclusions

NAWC concluded that the proposed program, as designed in this study, is technically feasible.

After careful review of the predicted costs associated with running the cloud seeding program, and after considering the potential yield as predicted in this study, NAWC has determined the following:

1. A ground-based program designed to target all 4 target areas, would exceed the American Society of Civil Engineers' (ASCE, 2016) recommended 5:1 benefit to cost ratio with a 10:1 benefit to cost.
2. A mixed program with both aerial and ground support would optimize production, but at a lower efficiency, yielding roughly a 7:1 benefit to cost.

It is concluded that the proposed cloud seeding program would be economically feasible and that the ASCE requirements that a proposed program would be both technically and economically feasible for the Santa Ana River Watershed would be met.

Questions and Answers

Throughout the course of this study, NAWC has engaged with personnel from SAWPA member agencies via, phone, email as well as during live and digital conferences. Throughout these engagements a number of questions have been asked regarding aspects of this study. NAWC has attempted to incorporate these questions, as best as possible, into the body of this study. For quick reference, many of these questions were included in APPENDIX F, with corresponding answers.

1.0 INTRODUCTION

1.1 Background

North American Weather Consultants (NAWC), received a Request for Proposals (RFP) followed by an executed contract to conduct a weather modification feasibility study for the Santa Ana River Watershed located in southern California. This RFP was issued by SAWPA on October 1, 2019 with the title Weather Modification Program. "The primary objective of the study is to determine the feasibility of a weather modification or cloud seeding program to increase precipitation and snowpack in the Santa Ana River Watershed".

There were five tasks to be completed in this study:

- Task 1 - Collection of Data.
- Task 2 - Selection of Target Areas.
- Task 3 - Development of Program Design and Seeding Increase Estimates.
- Task 4 - Perform a Benefit/Cost Analysis.
- Task 5 - Delivery of Final Report

1.2 General Description of Cloud Seeding

Clouds form when temperatures in the atmosphere reach saturation, that is, a relative humidity 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 a combination of water droplets, supercooled water droplets and ice crystals

In cold regions (< 0°C) of clouds, cloud water droplets may not freeze. The reason for this is the purity of the water droplets. In a controlled environment, pure water droplets can remain unfrozen down to a temperature of -39°C. As many clouds will never reach temperatures as cold as -39°C water droplets depend on impurities to induce freezing. Naturally occurring impurities often consist of tiny soil particles or bacteria. Cloud seeding is the process of introducing additional nucleating agents into storm systems to improve the efficiency of the nucleation process. Research has demonstrated that microscopic particles of silver iodide can be much more effective nucleating agents than naturally occurring freezing nuclei within a temperature range of about -5 to -15°C.

Once an ice crystal forms within a cloud, it will grow as cloud droplets around it add their mass to the ice crystal, eventually forming a snowflake. Ice crystals can also gain mass as they fall and accrete surrounding supercooled cloud droplets, a process known as "riming." Once heavy enough, these snowflakes can precipitate and fall to ground as either rain drops or snowflakes depending on air temperatures near the ground.

1.3 Critical Terms and Concepts

Automated High Output Ground Seeding (AHOGS) systems:

NAWC proprietary* real-time, remotely controlled equipment that makes use of burn-in-place flares to release high concentrations of seeding agents over a short period of time.

*Though the specific design and operational constructs of these flare systems are proprietary, other cloud seeding contractors are believed to have operated similar systems.

Cloud Nuclei Generator (CNG):

A generator that burns a solution of a particular seeding agent. Generally, these are ground based, manually operated units.

Convection:

This is the tendency of warmer air to rise and cooler air to sink under the influence of gravity. Convection plays an important role in the development of some cloud structures and is a defining attribute of some of our targeted storm systems.

Convective Bands:

An organized or semi-organized area of convective clouds that produces precipitation, often linear or banded in appearance. These storm types are of particular interest in cloud seeding, as they lift seeding agents efficiently and generally contain high concentrations of supercooled liquid water.

Ice Nucleation:

The process of water droplets suspended in a cloud freezing, forming ice crystals.

Inversion:

Referring to temperature, a layer of air in which temperature increases with altitude, as opposed to the more common decrease in temperature with increasing altitude. This is important as the principle characteristic of an inversion layer is the presence of static stability, such that very little vertical lift occurs below the inversion.

Orographic Effect:

As air near the surface is forced up and over mountain barriers, the air cools. As the air cools it can reach its saturation point (i.e.., 100% relative humidity) which results in the formation of clouds.

Orographic Lift:

Lifting of air masses by underlying mountainous terrain.

Nucleating Agents:

Impurities (naturally occurring or induced through the process of cloud seeding) that instigate the formation of water droplets or ice crystals.

Wind Direction:

In meteorology, the standard convention is for wind direction to be reported as the direction from which the wind is blowing. For example, a southwest wind would indicate the wind is blowing from the southwest, towards the northeast.

Seeding Criterium:

When analyzing storm characteristics to understand the potential effectiveness of cloud seeding, there are a few attributes that are critical to consider:

- Vertical profile of temperatures
- Wind: speed and direction at ground level and aloft
- Atmospheric stability, including temperature inversions
- Precipitation type and intensity
- Convective lifting/convection, which influences mixing and vertical dispersion of the seeding agent.
- Topography of the target areas and localized storm characteristics

1.4 Potential Target Areas

An early requirement in developing a cloud seeding feasibility study to augment precipitation is to identify potential target areas. Logically, the target areas should encompass regions in which the most useful precipitation occurs. In the case of the Santa Ana River Watershed the most useful precipitation in generating streamflow will be derived from locations that receive the highest amounts of precipitation. For the Santa Ana River Watershed, as is the case in many mountainous areas of the world, the highest winter season precipitation typically occurs at the highest elevations of the watersheds. This is due to an atmospheric phenomenon known as the “orographic effect”. This effect is produced when lower-level air accompanying winter storms is forced up and over mountain barriers.

Based upon this discussion, there are potentially four possible target areas that could be considered in the Santa Ana River Watershed. Figure 1.1 provides a map of these potential target areas that will be referred to as Northwest (NW), Northeast (NE), Southeast (SE) and Southwest (SW). The boundaries of these areas are based upon the 3,000-foot elevation contour and also on the barrier crests in the case of the NE and SE areas. One exception is the SW target area, where lower average elevations exist; this area was created using the 2,000-foot elevation contour.

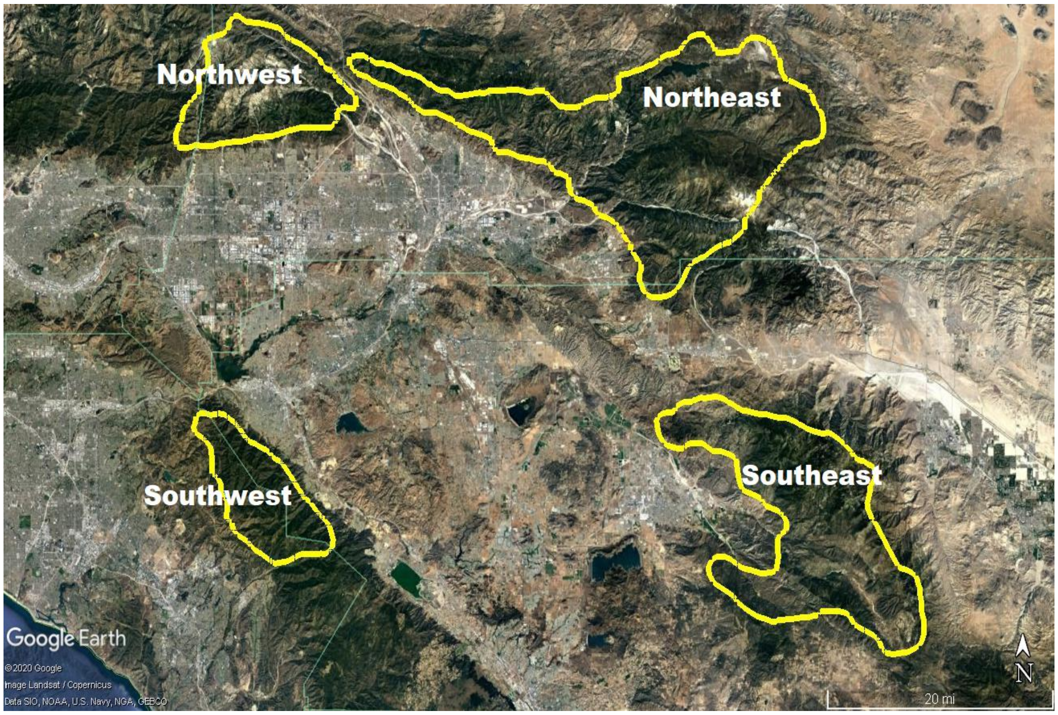


Figure 1.1. Potential Cloud Seeding Target Areas in the Santa Ana River Watershed.

2.0 CLIMATE

Southern California has a Mediterranean-type climate with warm, dry summers and cool, somewhat moist winters. Winter precipitation is somewhat sporadic and highly variable from one season to another. Average annual precipitation ranges from between 20-40” annually in mountainous areas (above about 2,000 to 3,000 feet in elevation), between about 10-20” in lower elevation coastal areas, less than 10” in desert areas and under 5” in the drier inland deserts.

Although higher elevation areas (and more inland areas) receive some occasional monsoonal or convective type shower activity beginning in July, the months of June and July are the driest on average. During the months of July – September monsoonal moisture, as well as occasional moisture surges from decaying tropical systems in the eastern Pacific (most common around September) leads to slight increases in the precipitation average, most pronounced for inland areas. The beginning of eastern Pacific frontal system activity in the fall results in continued increases in average precipitation. The greatest precipitation in general is during December – March, with the early season (December) precipitation events tending to be the warmest, having higher snow levels in general, than the remainder of this seasonal period.

Mountain snowfall is most common in mid to late winter, with the months of January through March having the greatest average snowfall. Most of this occurs above 5,000 feet in elevation, where a significant snowpack can accumulate. An accumulating snowpack is most common in areas above 7,000 feet in elevation, which often record between 100 – 150” of snowfall annually. Snowpack occasionally accumulates to 2 feet or more in depth in these areas. Snowfall is more sporadic below about 4,000 feet in elevation, with areas near 4,000 feet more likely averaging 20-25” of snowfall in a given season. Snow is more uncommon below 2,000 feet in elevation but does occasionally fall at or below this level. It should be noted that even the month of April can bring storm events cold enough to produce snowfall at relatively low elevations, partly related to the fact that the sea-surface temperature along the California coast reaches a minimum in the spring.

The four primary target areas of the Santa Ana River Watershed are distinct in terms of their geography and topographic features. The southwestern portion (Santa Ana Range), bordering Orange and Riverside counties, is by far the lowest in elevation of the four, generally topping near 4,000 feet in elevation, with a few peaks (such as Modjeska and Santiago) exceeding 5,000 feet. The portion of this range in the Santa Ana River Watershed above 2,000 feet elevation is approximately 15 miles long by approximately 7 miles wide. This area generates primarily winter runoff directly pertaining to rainfall events, with little to no accumulating snowpack under normal circumstances. Annual precipitation in this range is believed to be generally between 15-25”, although there is a lack of precipitation stations in higher elevation portions.

The northwestern portion (NW target area), bordering Los Angeles and San Bernardino Counties (mostly in the latter) encompasses a portion of the Central Transverse Ranges, to the west of the I-15 freeway. This portion of the watershed above 3,000 feet is a triangular area about 10-12 miles in scale, containing multiple peaks above 8,000 feet elevation. Most of this area receives about 25-35” of annual precipitation, as well as some significant snow accumulation in higher elevations. Runoff from this area reaches a general maximum from about December – April, with snowmelt in some seasons keeping streamflow elevated into May.

The northeastern portion (NE target area) in San Bernardino County encompasses the area of the Central Transverse Ranges east of I-15, extending down to I-10 north of Palm Springs. This is by far the largest of the four target areas in this study above 3,000 feet, with a length dimension (oriented northwest – southeast) over 35 miles and a width (for the Santa Ana River Watershed portion of the area) ranging from 2 miles on the northwestern side to about 20 miles in the much broader eastern portion. This eastern portion extends generally southward from Big Bear Lake and includes some very high terrain with some peaks reaching over 11,000 feet in elevation (such as San Gorgonia Mountain). This portion of the Santa Ana River Watershed generally receives between 20-40” of annual precipitation, including significant snowpack accumulation in some seasons at higher elevations. Runoff originating in this area appears to have a distinct peak around late March/early April, which is likely a combination of direct runoff from rainfall as well as snowmelt runoff. In some seasons, snowmelt contributes to runoff into May. This portion of the watershed is by far the largest contributor to runoff, with typical runoff 2-5 times that of the other three areas in the watershed.

The southeastern portion (SE target area) of the watershed, in Riverside County centered just to the west and southwest of Palm Springs, appears significantly drier than more northern areas despite an area of high elevation terrain. On the eastern side, there are portions above 8,000 feet in elevation with Mt. San Jacinto (on the eastern boundary) exceeding 10,700 feet. The overall target watershed area over 3,000 feet elevation is about 28 miles long (northwest to southeast dimension) and approximately 12 miles wide (northeast to southwest dimension). This area generally receives about 15-25” of annual precipitation, with a limited amount of high elevation area, over about 7,000 feet on the eastern side, as the only location that is likely to have any significant snow accumulation.

Figures 2.1 – 2.4 show annual precipitation patterns representative of each of these areas. These monthly plots were derived from long-term precipitation stations that appear to be most representative of their respective areas. The periods of record for these plots vary somewhat but are based on sites that appear to have the best long-term periods of monthly precipitation records. These graphs show a strong winter season (December – March) precipitation maximum overall, with the months of November and April also having some significant precipitation although generally half or less of the average of the other winter season months. A strong precipitation minimum is observed in the summer (especially June and July), with this being most pronounced in the more western areas closer to the coast. A minor monsoonal precipitation maximum is observed around July to September in the more eastern (inland) areas when showers and thunderstorms sometimes develop in these areas.

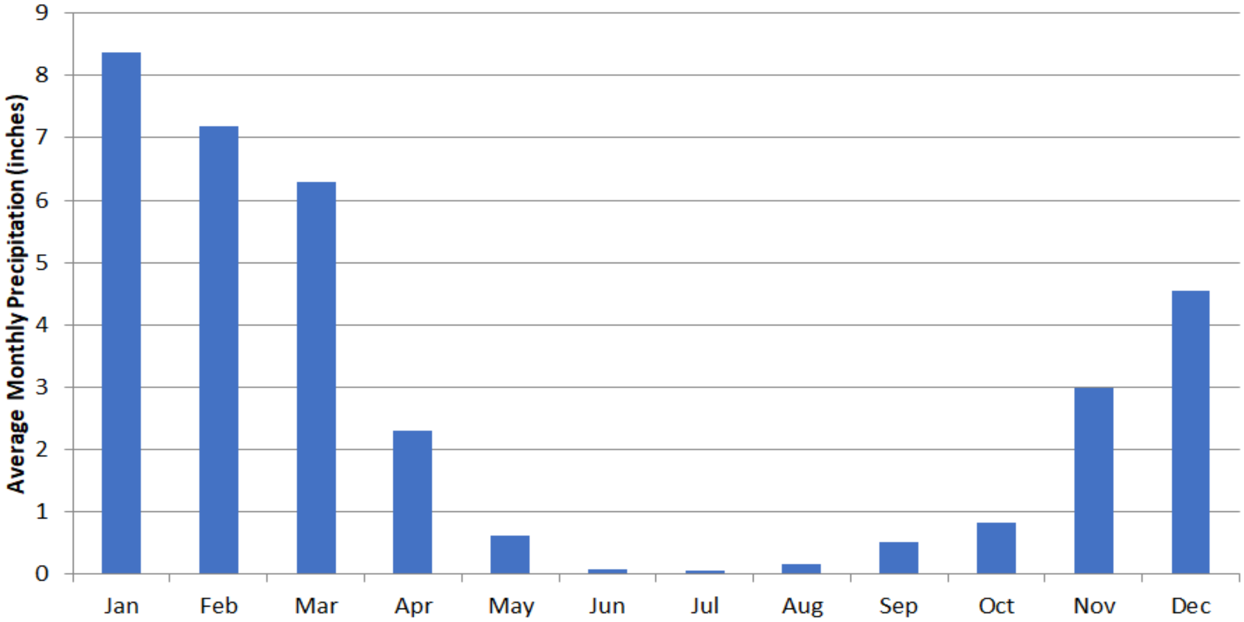


Figure 2.1. **Lytle Creek Range Station, 1942-2000 monthly precipitation averages, Northwest target area.**

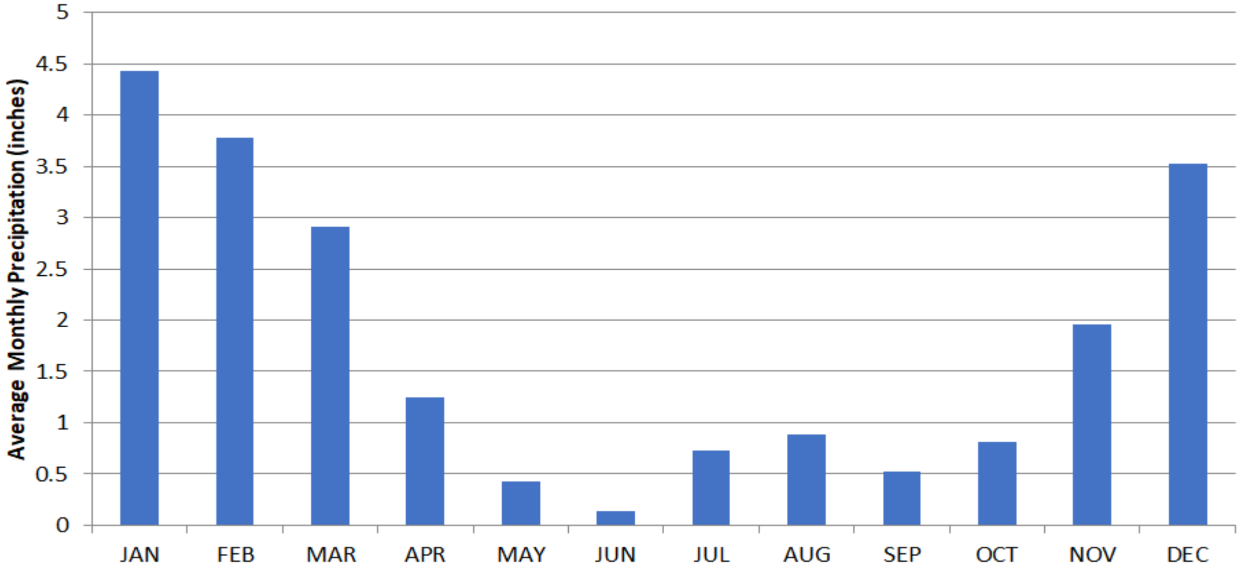


Figure 2.2. **Big Bear Lake, 1961-2019 monthly precipitation averages, Northeast target area.**

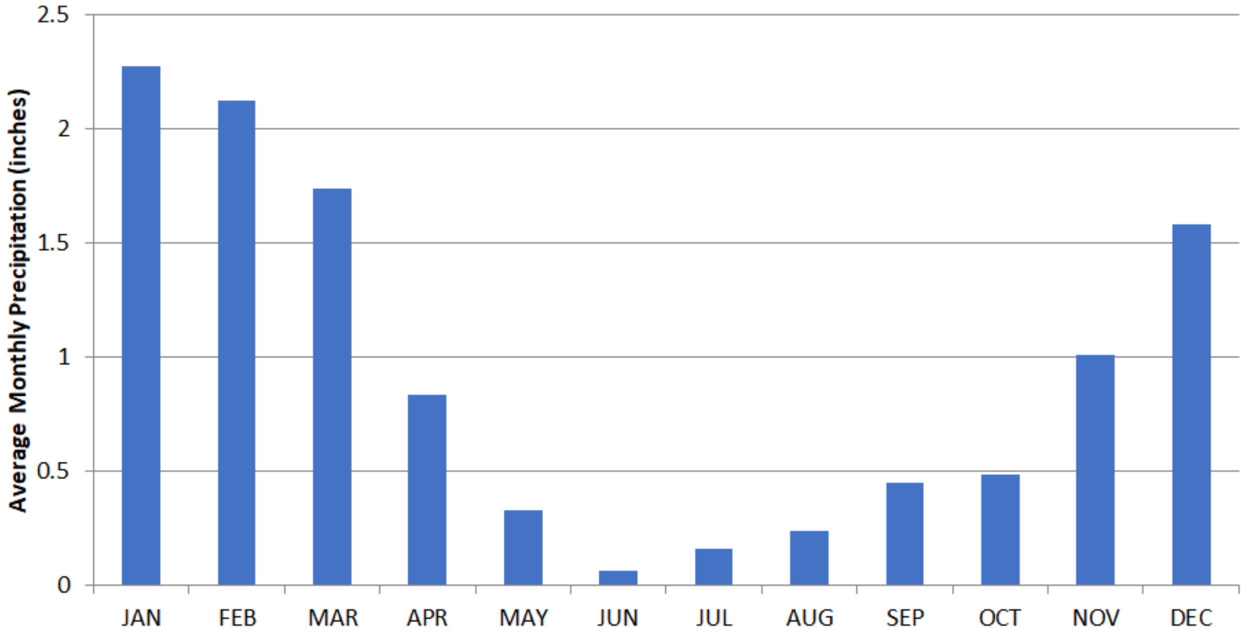


Figure 2.3. Hemet, 1943-2019 monthly precipitation averages, Southeast target area.

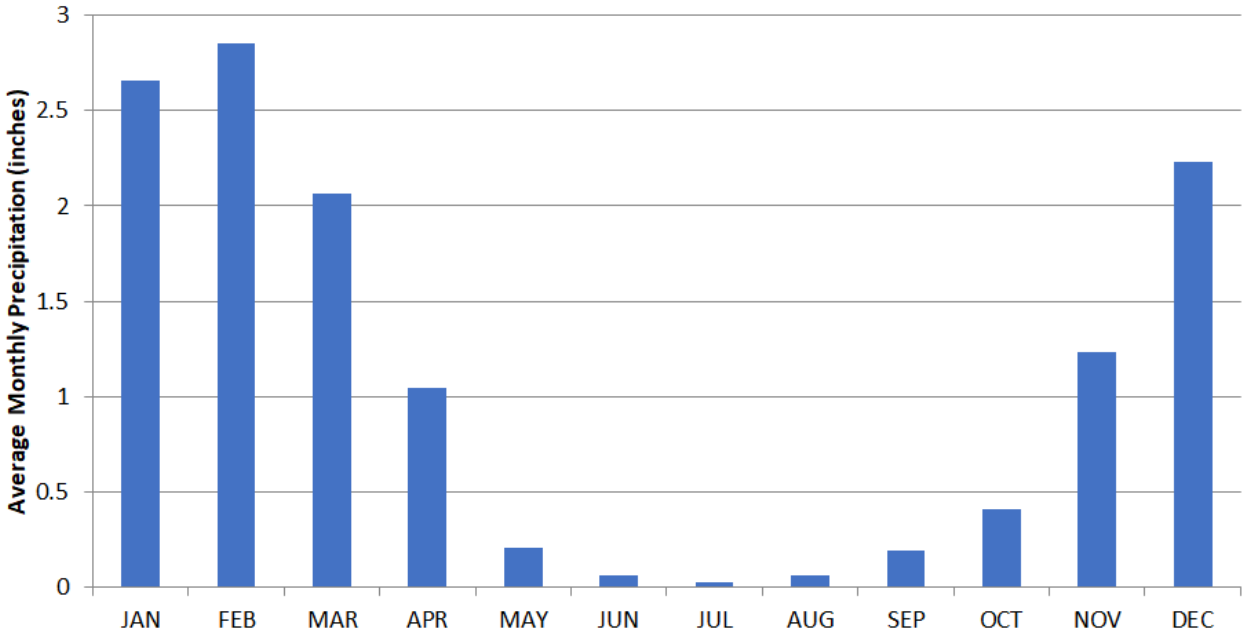


Figure 2.4. Santa Ana Fire Station, 1923-2019 monthly precipitation averages, Southwest target area.

3.0 PROGRAM DESIGN

A detailed operations plan should be developed by the Contractor selected to implement this a cloud seeding program to benefit the Santa Ana River Watershed. This plan would be customized specifically for the intended target areas. This plan would be available as a reference for all program personnel. It would include such topics as: operational period, personnel, equipment, maintenance, operations center, operational, procedures, models, seeding decisions, suspension criteria, communications and reporting.

The following discussions reflect the methods, equipment and general procedures that are typically implemented by NAWC to perform cloud seeding programs in California. The Contractors selected to participate in an RFP and ultimately to perform this work may propose different equipment or procedures. SAWPA will decide what types of equipment and procedures are in their best interest during the RFP process.

3.1 Technical Program Design

3.1.1 Brief Cloud Seeding Theory for Precipitation Augmentation

Clouds form when temperatures in the atmosphere reach saturation, that is, a relative humidity 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. They may attain sufficient sizes to precipitate 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 accrete surrounding 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 rain if surface temperatures are warmer than freezing.

Research conducted in the late 1940's demonstrated that tiny particles of silver iodide could mimic the natural process 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°C 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 sizes) have used silver iodide as the seeding agent. These programs are conducted to affect cloud regions that are -5°C or colder (e.g., "cold clouds") and 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 in winter stratiform or convective 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 which are typically some kind of salt (e.g., calcium chloride). These salt particles can form additional cloud droplets, which may add to the precipitation 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 which may then grow vertically 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 the surface temperature profile.

3.1.2 General Considerations

The ASCE 2016 publication entitled "Guidelines for Cloud Seeding to Augment Precipitation" states 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 SAWPA target areas offer an unusual mix of seeding potential from several different storm types based upon analyses performed for Tasks 1 and 2 in the Memorandum Report. Two of the more recognizable winter coastal California storm types were convection bands and orographically enhanced clouds. Other types indicated in this analysis are a blend of stratiform and convective types that probably contain similarities to the two more recognizable types. These two types will be discussed separately.

3.1.3 Convection Bands

There are some interesting cloud formations that affect the coastal areas of the western United States. These features have been referred to as convection or convective bands which are embedded in winter storms that impact these coastal areas. They are similar to summertime squall lines that impact our mid-western states in the summertime.

The proposed seeding program for the four SAWPA target areas has a unique advantage in regards to the above ASCE recommendation since a well-funded winter research program, Santa Barbara II, Phases I and II, was conducted during the winters of 1967-1973 (Brown et al., 1974; Griffith et al., 2005). The Santa

Barbara II research program consisted of two primary phases. Phase I consisted of the release of large amounts of silver iodide, using seeding flares, from a single ground location near 2,500 feet MSL located in the Santa Ynez Mountains northwest of Santa Barbara, California. These silver iodide releases were made as “convective bands” passed overhead. These convection bands were shown to contain supercooled cloud droplets, the targets of glaciogenic cloud seeding programs. The releases were conducted on a random seed or no-seed decision basis in order to obtain baseline non-seeded (natural) information for comparison. The amount of precipitation that fell from each seeded or non-seeded convective band was determined at a large number of precipitation gauge locations. Average convective band precipitation for seeded and non-seeded events was calculated for each rain gauge location. Results of seeding from the ground were calculated as ratios of average seeded band precipitation versus the non-seeded band precipitation. Ratios greater than 1.0 were common. A ratio of 1.50, which covered sizable areas downwind of the seeding site, suggested a 50 percent increase in precipitation from seeded convective bands compared to non-seeded bands.

In a similar experiment, Santa Barbara II, phase II, an aircraft was used to release large amounts of 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. Again, the ratios of average precipitation from seeded to non-seeded bands were calculated, and a large area of higher precipitation was indicated in seeded convective bands compared to non-seeded convective bands.

A study of the contribution of "convective band" precipitation to the total winter precipitation in 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. 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 NAWC assumes the convective bands would have contributed one half of the winter season's rainfall.

It is significant that the Santa Barbara County Water Agency has contracted for operational cloud seeding programs to be conducted, targeting convection bands, in the County most winter seasons since 1981. NAWC has conducted most of these programs for the Agency. These programs have been based upon the design and results from the Santa Barbara II research program (Griffith et al., 2005). A WMA Journal of Weather Modification paper that contained a target/control evaluation of this long-term operational program provided estimated average increases in seasonal precipitation ranging from 9 to 21% (Griffith, et al., 2015).

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. Seeding these bands with silver iodide either from the ground or air can increase 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.

Even though the Santa Barbara II research program was conducted approximately 45 years ago, it is NAWC's professional opinion that it offers the most relevant information for the design of precipitation enhancement programs for this area that are designed to seed convection bands. There has not been any other winter weather modification research program conducted in the coastal areas of California since Santa Barbara II. NAWC's Memorandum Report, covering Tasks 1 and 2 indicated that convection bands were present in some winter storms that impact some if not all the proposed target areas.

Convective bands contain areas of significant vertical lift and highly productive rain events. Vertical lift can result in the transport of seeding material released from the ground reaching effective levels for the seeding material can become active. To take advantage of these events, NAWC recommended that some ground-based remotely operated silver iodide seeding flare sites be included in the design of the SAWPA program. NAWC's design for this type of unit is known as Automated High Output Ground Seeding systems (AHOGS). A photo of one of these units is provided in Figure 3.1. Flares manufactured by Ice Crystal Engineering (ICE) of North Dakota are frequently used in these units.

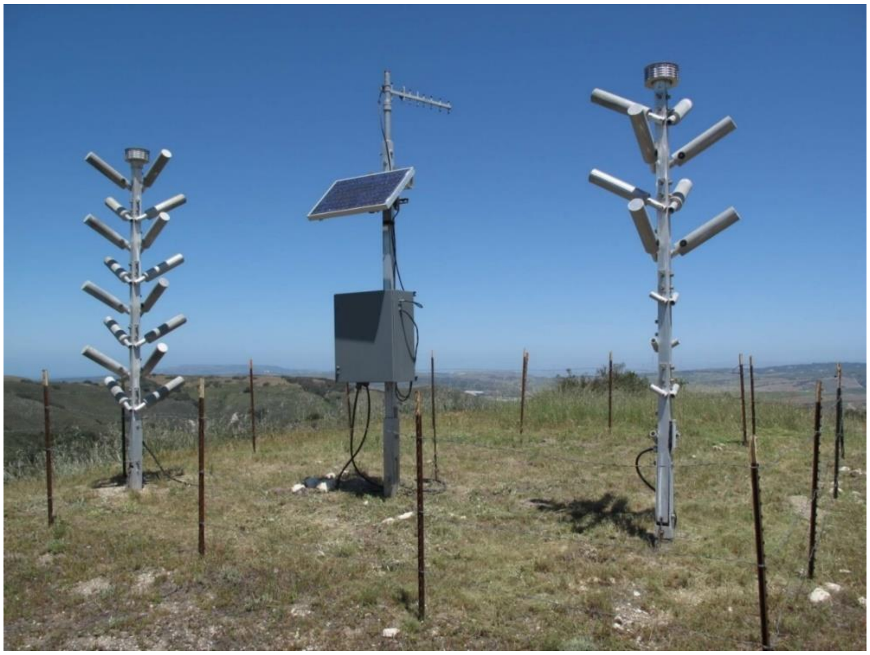


Figure 3.1. Photo of a NAWC AHOGS Site

3.1.4 Orographic Clouds

There is a well-known orographic effect, which is caused when moist air is forced over mountain barriers and cools as it rises over the mountains. When air reaches the saturation point, water vapor condenses into liquid form creating clouds. This effect often occurs in the wintertime over mountain barriers. Sometimes the resulting clouds only form over the mountain barrier. At other times, clouds have already formed as organized storms approach a mountain barrier, but the orographic effect enhances these cloud formations. Research has shown that this orographic effect frequently results in the accumulation of supercooled cloud droplets, the target of glaciogenic cloud seeding (e.g., Griffith et al., 2013) along the upwind slopes of mountain barriers. Figure 3.2 provides a conceptual visualization of this accumulation zone. This was the case with the Sierra Cooperative Pilot Project (SCPP) conducted over the American River Basin in the central Sierra Nevada (Reynolds, 1988) and in a research program conducted over the Wasatch Plateau Mountains in central Utah (Super, 1999). There were a number of other winter orographic research seeding programs conducted in the western United States, a number of these were funded under the Bureau of Reclamation's "Project Skywater" research program.

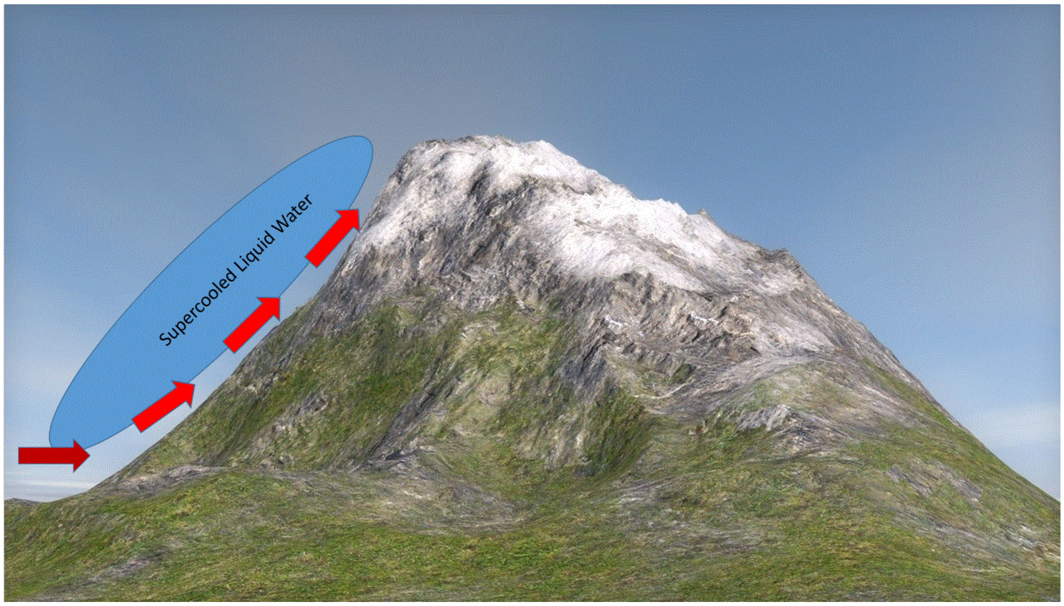


Figure 3.2. **Conceptual Model of the orographically-induced supercooled water accumulation zone.**

The orographic effect results in more naturally occurring precipitation falling over mountain barriers than over the upwind and downwind valleys thus presenting prime storm conditions for seeding since any additions to these naturally higher precipitation amounts in mountainous areas can likely result in additional runoff from these mountains; perhaps immediately if the precipitation falls as rain or delayed runoff when snow packs melt.

This reasoning led to some of the earliest cloud seeding programs in the U.S. being developed over the Sierra Nevada Mountains in California, some dating back to the 1950's. Winter orographic cloud seeding programs have been conducted over numerous mountain barriers throughout the west. A comprehensive report (Silverman, 2010) evaluated eleven long-term operational cloud seeding programs conducted over the Sierra Nevada Mountains in California. These evaluations indicated that most programs targeting the upwind slopes of the mountains indicated positive seeding effects, several being statistically significant. Operational winter operational orographic cloud seeding programs have been conducted for many years in several western states (e.g., Colorado, Idaho, Nevada, Utah and Wyoming). The seeding modes employed on these programs have included ground-based seeding generators and cloud seeding aircraft. NAWC has used manually operated silver iodide generators, sometimes referred to as cloud nuclei generators (CNGs), in numerous winter programs conducted in several western states, for many years. NAWC, in the Memorandum Report, recommended that a network of CNGs be installed to seed the SAWPA target areas. CNGs would be sited at local residents and/or businesses and these residents called by the program meteorologist when the unit should be activated and deactivated. Figure 3.3 provides a photo of one of these units. NAWC recommends that 20-25 grams of silver iodide be released for each hour of operations from one of these or similar units. NAWC has also recommended that a cloud seeding aircraft be employed on the SAWPA program to seed orographic cloud conditions that impact the SAWPA Northeast target area. Figure 3.4 provides a photo of such an aircraft equipped with silver iodide seeding flares.

Figure 3.3. **Example of a NAWC Manually Operated Cloud Nuclei Generator**

Figure 3.4. **Example of a Cloud Seeding Aircraft Equipped with End Burning Silver Iodide Flares**

3.2 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 (responsible for the supervision and overall success of the program), 2) a project meteorologist, 3) a pilot, 4) a local part time technician, and 5) CNG operators. The supervisor and meteorologist could operate from the contractor's headquarters. The pilot would be stationed at a suitable full-service airport in proximity to the target area. NAWC recommends that a Weather Modification Association (WMA) Certified Manager (CM) or American Meteorological Society Certified Consulting Meteorologist (CCM) be the program manager and that a WMA Certified Operator (CO) serve as the project meteorologist.

3.2.1 Project Meteorologist

A dedicated project meteorologist will manage the day-to-day operations of the project. He/she will maintain daily logs of project activities. The meteorologist's responsibilities include several tasks. First and foremost, the primary responsibility of the meteorologist will be to conduct weather modification activities for the Santa Ana River Watershed. This includes submitting to the client a daily forecast each weekday for the target area, (transmitted via e-mail). The project meteorologist's duties also include computer archiving of meteorological data, ground generator seeding times and, if seeding aircraft are used, aircraft flight tracks superimposed on radar displays for all seeded storm periods. The project meteorologist will ensure that each component of the project is maintained in full operational readiness. This includes making sure that the aircraft and ground-based seeding sites are serviced appropriately and kept in operational status, as well as keeping track of seeding start/stop times and keeping notes on meteorological conditions and operational decision making. The project meteorologist will track usage of the ground-based seeding sites and coordinate refills by the project field technician and the propane supplier. The project meteorologist will be responsible for the operation of the two AHOGS sites remotely, and will communicate with the operators of the manual CNG's. The project meteorologist will also be responsible for written (electronic) monthly reports for each operational month submitted to SAWPA, and possible presentation of brief project operational summaries at monthly Board meetings if requested by SAWPA. The project meteorologist will keep the program manager informed of the status of the field program.

3.2.2 Pilot

The duties of the pilot are to operate the seeding aircraft during appropriate storm periods, and to make sure that the aircraft is always at full operational status. This includes servicing, refilling and testing of the seeding systems. The pilot will also need to inform the project meteorologist of any problems with the airborne seeding systems, when the aircraft has any mechanical problems, or when any other aviation-related factors may cause potential interference with the conduct of operations. The pilot must be reachable via telephone 24/7 and able to fly seeding missions on short notice. He/she must coordinate with the project meteorologist any potential travel away from the project area. The pilot also coordinates the project flight plans and activities with the appropriate FAA authorities. This includes renewal of waivers or permits, approvals for the predetermined flight tracks, and coordination of flight procedures. The pilot is also responsible for coordinating any required aircraft maintenance with the project meteorologist and the aircraft owner.

3.2.3 Field Technician

The main responsibility of the field technician is the installation and maintenance of the ground generator network. This includes refilling the CNG's with seeding solution on request by the meteorologist and taking care of other ground based CNG servicing issues as well as replacing expended flares and maintenance of the AHOGS systems.

3.2.4 CNG Operators

Each of the CNG sites is operated by someone who lives and/or works at the location. The CNG operator is contacted via phone or email by the project meteorologist with operational on/off instructions. The operator will also inform the project meteorologist if his/her CNG malfunctions or is out of service for any reason. If at any point there is a major problem with the seeding generator, the operator will turn it off and inform the project meteorologist of the problem immediately. The project meteorologist will then notify the field technician of the service needs.

NAWC recognizes that there will be down time with CNG's, operators will occasionally be unavailable or unresponsive, and machines may fail or require maintenance. It is important to note, that adequate redundancies have been incorporated into the design of this program, to accommodate for occasional missed CNG operations.

3.3 Weather Radar

The National Weather Service (NWS) NEXRAD radar sites in southern California (KSOX – Santa Ana Mountains; KVTX – near Ojai; KNKX – near Poway) will be used in the operation of the cloud seeding program as they provide good coverage of the target areas. These radars will provide valuable information regarding the structure, intensity, movement, and evolution of precipitating cloud systems in addition to wind speed and direction within the precipitating echoes. An upgrade to dual-polarization capabilities within the past decade allows the radar to observe clouds using both horizontal and vertical waves, providing additional information about hydrometeors (e.g., identification of precipitation types) and non-weather targets. Real-time radar data are key in operational decision-making for seeding modes and tracks, to help optimize the seeding releases. The NWS is responsible for all the necessary support for the radar including operation, calibration, spare parts, and maintenance.

3.4 Seeding Modes

Ground-based seeding will be utilized to affect the target areas. The placement of twelve Cloud Nuclei Generators (CNGs) adjacent to three of the target areas and two Automated High-Output Ground Seeding (AHOGS) systems adjacent to the SW target area will help ensure dense coverage of seeding throughout the watershed. As with airborne seeding operations, the CNGs and AHOGS are activated in areas upwind of the target areas during storm events (generally southerly to westerly flow situations). Due to the orientation of the mountain barriers, a westerly to southwesterly flow is the most favorable direction for precipitation and provides the best orographic uplift. Therefore, the CNGs and AHOGS are located to the south and west of the target areas feeding the watershed. One of the CNGs, at Strawberry Peak, is located where it can be utilized in northwesterly flow situations. Figure 3.5 shows the recommended ground seeding site locations and their site IDs. Table 3.1 provides basic information for these sites. The generators will emit silver iodide particles. Nucleation is achieved via the condensation-freezing process. Two of the ground sites are AHOGS systems, used primarily for the seeding of approaching convective bands that are common closer to the coast. The AHOGS flares are similar to those used in airborne seeding.

The array of ground-based seeding sites should be used liberally. Use of multiple sites helps assure adequately high concentrations of nuclei in the seeding plumes and horizontal plume overlap over the higher terrain. If use of a given CNG or AHOGS could conceivably have a positive effect, it should be activated. Use of the HYSPLIT plume dispersion model, described in Section 3.8 can be helpful in assessing likely seeding plume trajectories. Keep in mind that the seeding plumes are not straight lines as may be depicted by some dispersion models. Rather, the seeding plumes are quickly distorted due to the effects on low-level airflow caused by the complex terrain. Also keep in mind that many storms are very moisture rich. It is essentially impossible to over seed most storms. NAWC's local field technician will keep the ground generator network in operations-ready status as directed by the project meteorologist.

Airborne seeding operations will be coordinated between the project meteorologist and the seeding pilot using VHF frequency 122.85. Wing-mounted flare racks containing silver iodide flares will be used, with flares burning over a 4-5-minute period, producing plumes of ice nuclei upwind of the target area. Each flare, manufactured by ICE, contains 16.2 g of silver iodide. Airborne seeding operations involve flying a predetermined track, shown in Figure 3.6 to intercept clouds that are moving into the target area. The track will be utilized to achieve proper placement of the silver iodide particles relative to the watershed and into the area of higher supercooled liquid water concentration. Studies have shown that the warmest in-cloud temperature for nucleation of supercooled liquid water droplets by the silver iodide particles is near the -5°C level.

3.5 Ground Seeding Site Locations and Airborne Seeding Tracks

For the purposes of this feasibility study, several winter seasons, beginning with 2010-2011 and ending with 2017-2018 were reviewed and storm periods noted as described in section 4.1 of this report. A total of 58 storm events were identified during a five-season period. Various parameters, such as mid-level wind speeds and temperatures (e.g., 850 mb/approx. 5000 feet MSL; 700 mb/approx. 10,000 feet MSL) were collected along with radar data showing the evolution of precipitation during these storm events as well as hourly precipitation from various sites. Having developed a base of information from all storm events, potential ideal sites for the location of ground-based Cloud-Nuclei Generators (CNGs) and AHOGS (Automated High Output Ground Seeding systems) were identified using Google Earth. This was done for each of the four target areas within the Santa Ana River Watershed identified earlier in the report (see section 1.4).

Sites were selected based on their common upwind location from their target areas, with the vast majority of sites located to the south through west of their intended target areas. Locations were based upon a predominant wind flow from the southwest at 850 mb (approximately 5,000 feet) as documented in a wind rose in section 4.1 (Figure 4.5). Accessibility to the site was also taken into consideration, with many locations either fenced off or on private property such that the general public would not have easy access. Should a program eventually come to fruition, more or less sites may actually be used for targeting in the different areas of interest; for this study, a total of 14 ground-based seeding sites (2 AHOGS, 12 CNGs) were selected for the four target areas in the Santa Ana River Watershed, locations are shown in Figure 3.5. In practice, the AHOGS sites would primarily be activated during the passage of convective bands as is done by NAWC on a long-term cloud seeding program conducted for the Santa Barbara County Water Agency (Griffith et al., 2005)

The AHOGS sites were chosen based on their location close to the coast where convective bands were most common based upon the analyses of the 58 discrete storm events and would be most effectively seeded from such a unit. The remaining CNG sites were ideal for seeding stratiform and upslope/orographic or convective storm events. Figure 3.5 graphically provides these locations in relation to the intended target areas. Table 3.1 provides the digital locations and elevations of these sites.

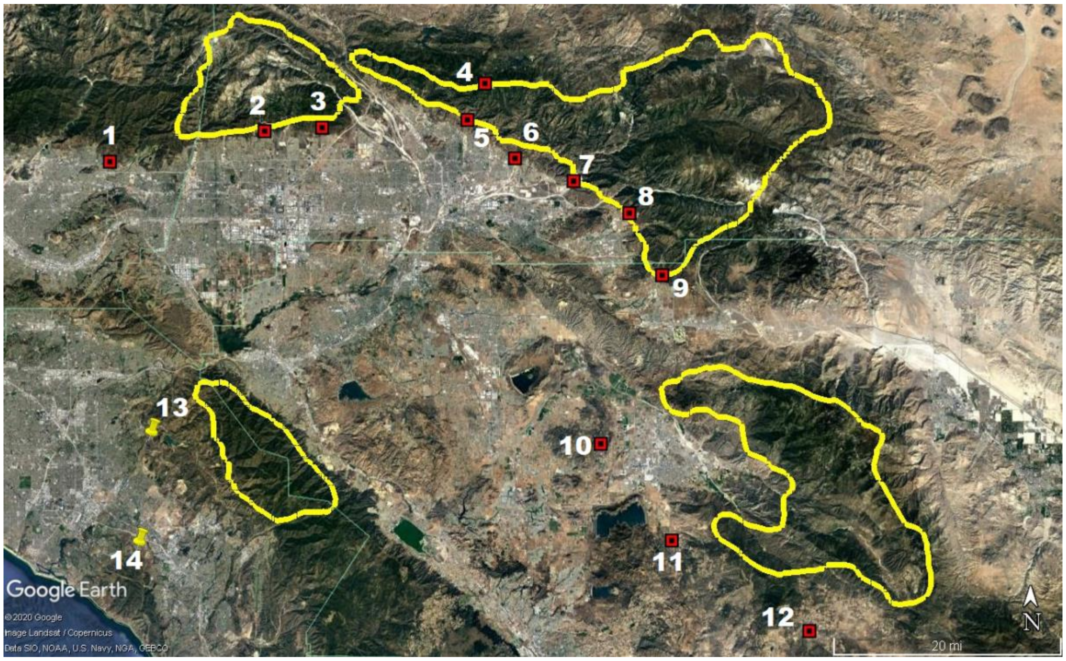


Figure 3.5. Location of ground seeding sites for each of the target areas. Red squares are CNG sites, while yellow pushpins are AHOGS sites. Numbers correspond to locations in Table 3.1.

Table 3.1
Locations and Elevations of Ground-based seeding sites
*** indicates AHOGS sites**

Site Name	Elevation (ft)	Latitude (DMS)	Longitude (DMS)	Latitude (DD)	Longitude (DD)
1 - Wildwood Ranch	1287	34° 08' 03.95" N	117° 48' 50.88" W	34.134431	-117.81413
2 - Deer Canyon	2641	34° 10' 23.47" N	117° 34' 24.85" W	34.17317	-117.57355
3 - San Sevaine Canyon	2462	34° 10' 39.96" N	117° 29' 06.23" W	34.177804	-117.48508
4 - Strawberry Peak	6151	34° 13' 54.84" N	117° 14' 03.72" W	34.231898	-117.23437
5 – Arrowhead Springs	1624	34° 11' 16.79" N	117° 15' 42.23" W	34.187996	-117.26173
6 - City Creek	1548	34° 08' 21.73" N	117° 11' 18.79" W	34.139369	-117.18855
7 - Seven Oaks Reservoir	1996	34° 06' 37.22" N	117° 05' 54.89" W	34.110338	-117.09858
8 - San Felipe Olive	3284	34° 04' 09.48" N	117° 00' 48.16" W	34.069299	-117.01338
9 - Edgar Canyon	3236	33° 59' 26.83" N	116° 57' 47.67" W	33.990784	-116.96325
10 – Hemet	1864	33° 46' 37.58" N	117° 03' 26.16" W	33.7771	-117.05727
11 - Rancho Armendariz	1837	33° 39' 15.10" N	116° 56' 55.39" W	33.654202	-116.94872
12 – Cahuilla Casino	3702	33° 32' 23.21" N	116° 44' 24.29" W	33.53978	-116.7401
13 - Handy Creek*	825	33° 46' 35.50" N	117° 45' 14.86" W	33.77637	-117.75417
14 - Shady Canyon*	640	33° 38' 10.35" N	117° 46' 22.08" W	33.636197	-117.77281

In addition to ground seeding sites, airborne seeding was considered as well. Aircraft seeding, utilizing either solution generators or seeding flares, is another seeding mode used on winter cloud seeding programs. Seeding flights would need to be conducted under Instrument flight rules (IFR) and would be under FAA control to maintain separation between the seeding aircraft and other commercial, military or private aircraft. If seeding flights could be conducted under visual flight rules (VFR), then the pilot of the seeding aircraft could maintain separation from other aircraft flying in the same airspace. This would not be the case in most seeding situations due to the presence of low and middle cloud decks. Storm winds at appropriate flight levels during potential seeding events are expected to be blowing from southerly to northwesterly directions. Flights would need to be conducted upwind of the intended target areas to allow time for the nucleation, growth and fallout of the augmented precipitation in order to fall within the intended target areas. Flights would likely be flown at the -5°C level (the average -5°C height from the storm period analysis was approximately 11,000 feet).

The average wind directions at the 700 mb level (approximately 10,000 feet) were from the southwest; that would mean that seeding flights would need to be conducted over the Los Angeles Basin to impact the intended target areas. There are a number of major commercial as well as private airports in the Los Angeles Basin. It may be difficult to get FAA approval for seeding flights during times of high traffic; unlike typical flights that quickly leave crowded airspace, seeding flights typically repeat the same flight track for an extended period of time. Such flights are likely to intersect take-off and landing zones for other aircraft since typical flight levels would be at relatively low altitudes over the Los Angeles Basin. Typical aircraft used on programs of this type include Cessna 340's, 414's, 421's; Piper Navajo and 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.

A potential flight track to the south of the northeastern target area was developed, shown in Figure 3.6. It was chosen considering that most storm events contain south through southwest flow aloft, and the position of this flight track would be ideal for aircraft seeding properly targeting clouds over the northeastern target area, which, overall, provides the highest amount of runoff of the four target areas and would see the greatest benefit from an aerial program.

The potential to conduct aircraft seeding to the north of the Los Angeles Basin over an area that would experience fewer commercial aircraft traffic was considered by NAWC. There were some storm periods that exhibited WNW wind flow at the 700 mb level (the likely altitude of aircraft seeding). Under these conditions it was surmised that aircraft seeding could be feasible, designed to impact the NE target area. This possibility was explored using the HYSPLIT model, but as will be mentioned in the summary, output from the model indicated that seeding plumes were not ideally transported into the target area until after the storm event was over.

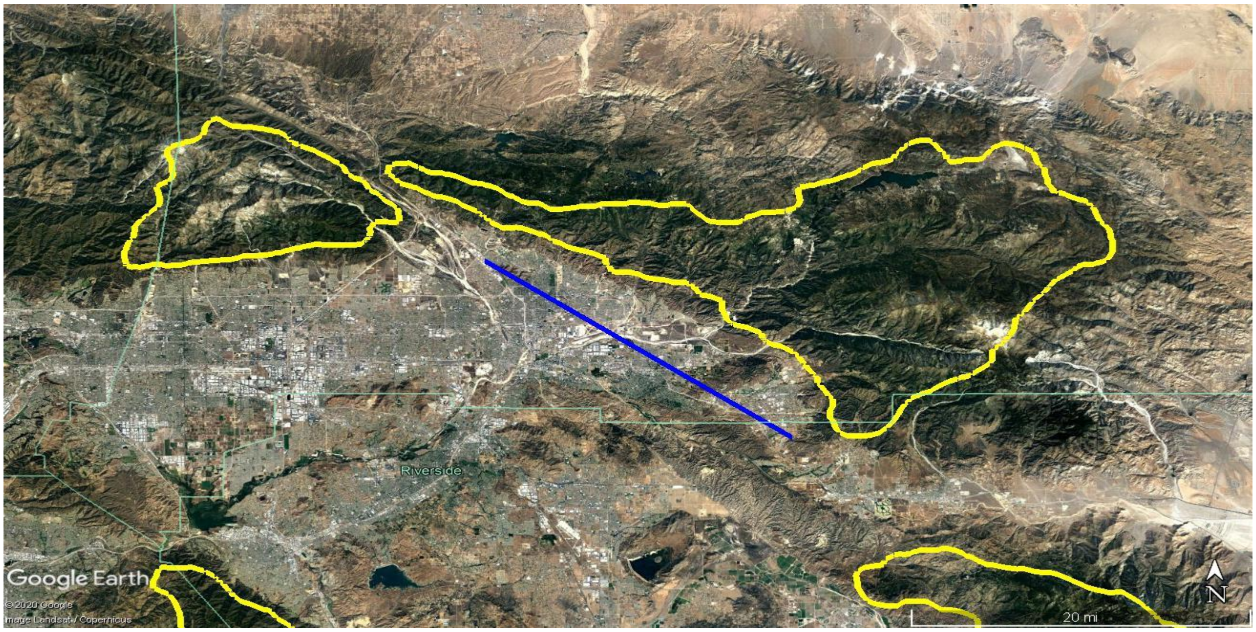


Figure 3.6. **Location of a potential airborne seeding flight track, in blue.**

Once potential seeding sites were selected for each of the target areas, the next step was to utilize the HYSPLIT model to determine how seeding plumes from each location would be predicted to impact the target area under varying storm conditions. As previously mentioned, 58 storm events were analyzed between the 2010-2011 winter season and the 2017-2018 winter season. From these, a subset of 11 events which represent the different storm structures experienced in the SAWPA areas of interest were chosen for HYSPLIT modeling. Archived model data from the subset of storm events were collected and the model was set up and run during periods where it was determined that seeding operations would have been feasible. For brevity, only two cases will be shown here, but HYSPLIT data from other cases are provided in Appendix D.

3.5.1. March 7, 2016

A cold upper level trough moved across the state during the day. There were two bands of precipitation as the trough pushed through: the first early in the day and the second later in the afternoon. 700 mb temperatures fell from -5°C to -11°C as the cold core of the storm neared, while 850 mb temperatures dropped from 2°C to 0°C. Winds at low and mid-levels varied from southerly near the surface to west-northwesterly at mid-levels.

Figure 3.7 shows a NEXRAD radar image at 0730 PST depicting the first band of precipitation moving into the Santa Ana River Watershed region. Figure 3.8 shows the HYSPLIT one-hour run of all 14 ground-based seeding sites and their projected plumes, valid at 0800 PST. Note that most sites are properly targeting their respective target areas. The meteorologist, having a good idea of the wind field in the area at the time of the event, would have most likely not chosen to run all sites, particularly sites north of the two northern target areas. Figure 3.9 shows a vertical cross section of a two-hour long plume originating from the two sites targeting the southwestern target area valid at 1600Z (0800 PST). These sites are theoretical AHOGS sites which would be activated during convective band passages, where the vertical dispersion of silver iodide particles would be enhanced through convective updrafts on the band's leading edge. Note the height of the plume in the lower panel at that point, indicated in meters above ground level (AGL). The top of the seeding plume is reaching near 3000 m (9840 feet) AGL, which, on this day, was above the height of the -5°C level and thus at sufficiently cold temperatures to initiate ice nucleation. Even though the particle concentrations are less near the top of the predicted plumes, this feature is offset since the activity of silver iodide ice nuclei are known to exponentially increase with decreasing temperatures based upon cloud chamber tests.

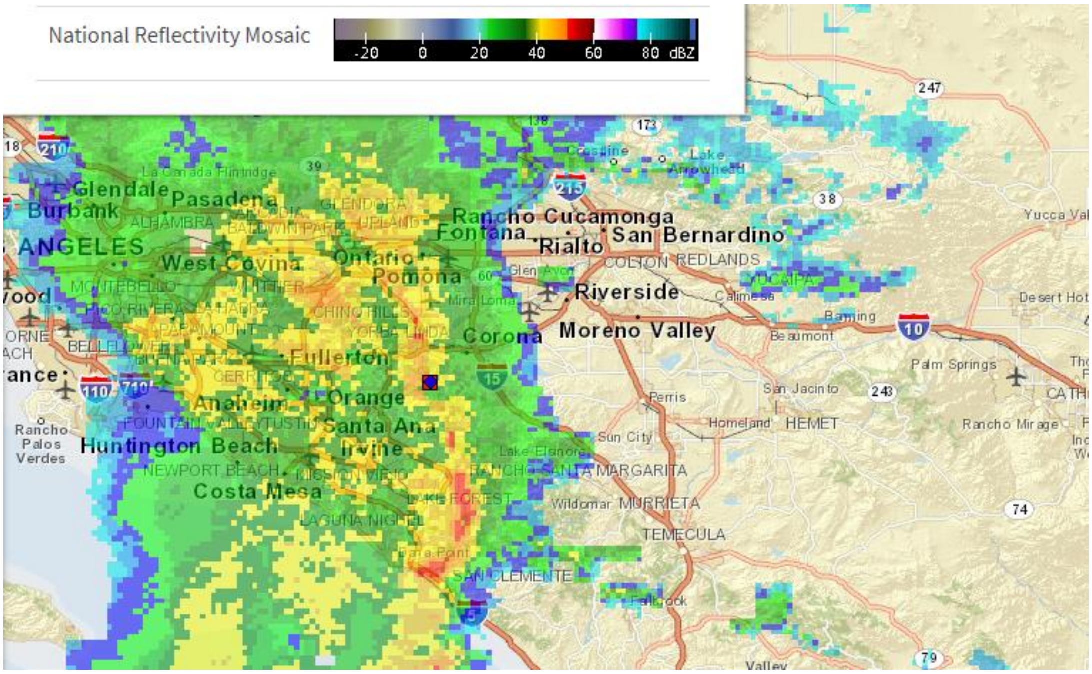


Figure 3.7. National Weather Service NEXRAD Radar image from 0730 PST on March 7, 2016.

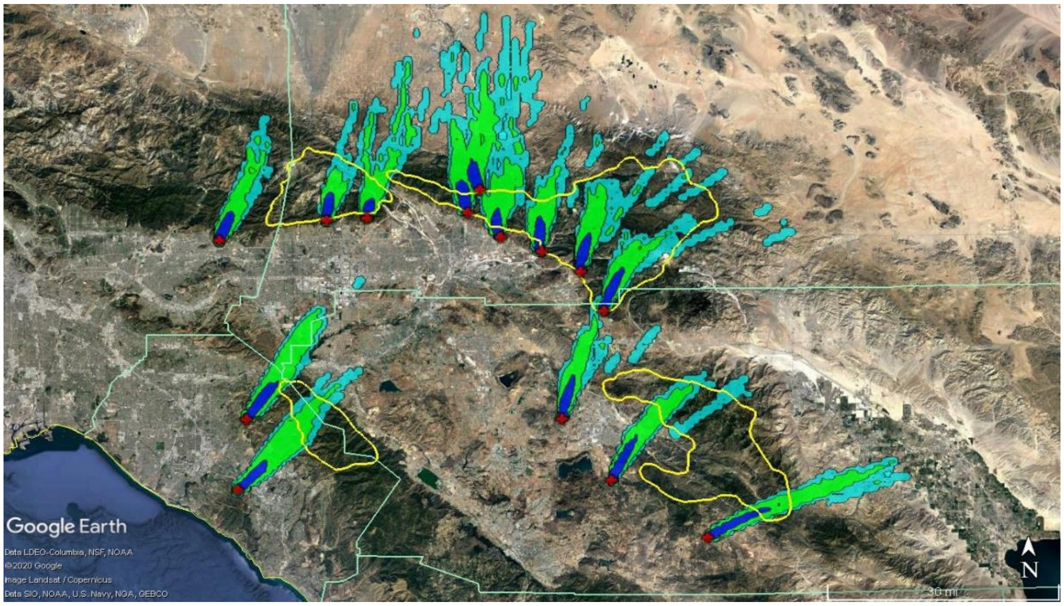


Figure 3.8. **HYSPLIT one-hour projected plume dispersion from all 14 ground-based seeding sites (red crosses), valid at 0800 PST on March 7, 2016. The blue colors indicate highest concentrations of particles, with green and cyan areas indicating lower concentrations. Yellow outlines are the four target areas.**

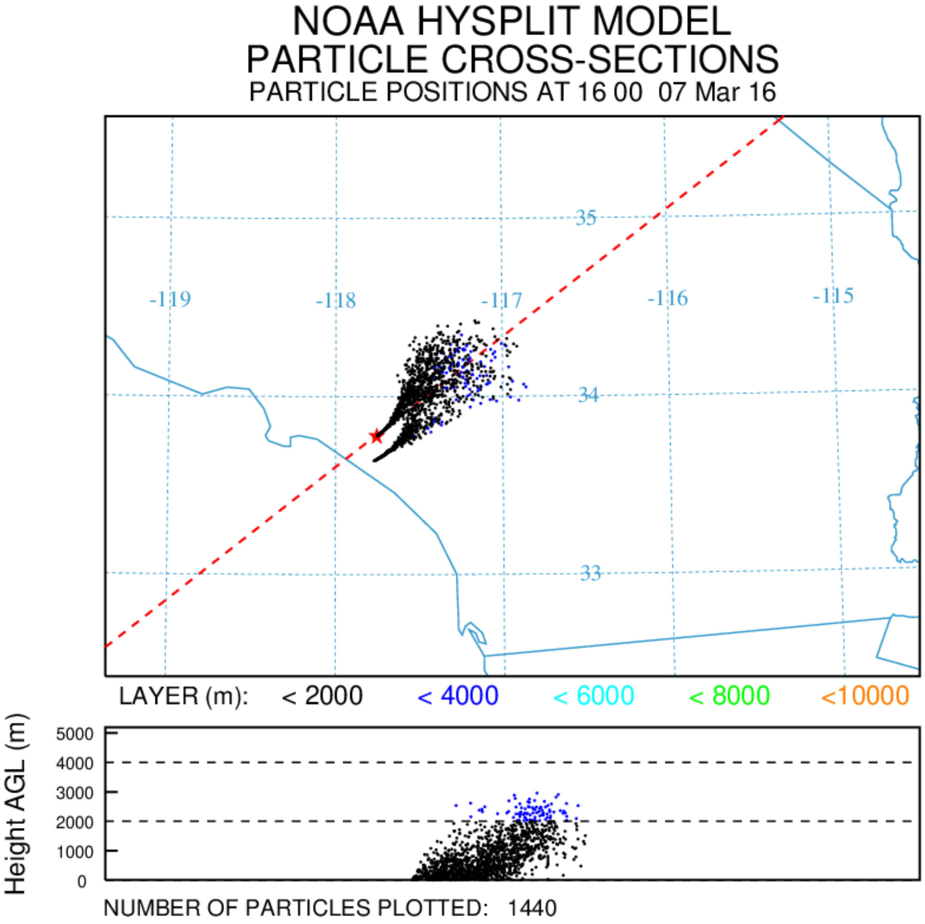


Figure 3.9. **HYSPLIT two-hour plume projected dispersion for two sites targeting southwestern target area, valid at 1600Z (0800 PST) on March 7, 2016. Top map shows horizontal dispersion, bottom image shows vertical distribution of particles, with y-axis indicating height in meters above ground level.**

3.5.2 January 9, 2018

A cold-core upper low, that had merged with a subtropical disturbance, was pushing into southern California during the day. Abundant moisture associated with the system entered the area, with scattered areas of rain. As the center of the low made its closest approach to the SAWPA area from late afternoon into early evening, a period of heavier precipitation and colder air aloft moved into southwestern California. 700 mb temperatures by the latter part of the afternoon had fallen to -6°C with 850 mb temperature around +3°C. Winds were generally from the southwest to west-southwest aloft, and southerly at the surface.

Figure 3.10 shows a NEXRAD radar image from 1600 PST, indicating an area of moderate precipitation covering a good portion of the Santa Ana River Watershed. Since it appeared that this would have been a seedable storm event (indeed, seeding operations had occurred earlier further up the coast in Santa Barbara County), ground generators and a potential seeding flight would have been commissioned. Figure 3.11 shows a two-hour projected plume dispersion from HYSPLIT, valid at 1800 PST. Note that some of the plumes were not directly targeting their respective target areas, but as mentioned previously, the meteorologist would have had a good knowledge of the predicted wind fields and may not have activated all generator sites. Figure 3.12 shows a one-hour projected plume dispersion from the suggested flight track, valid at 1700 PST. Plume coverage over the northern target areas appears to be excellent. It is worth noting that, since the plane would be flying at approximately the level where the temperature was at or near -5°C, the dispersed nuclei would likely be activating immediately with the supercooled water droplets in the clouds over the target areas creating ice crystals, so they would likely not continue to pass north/northeast of the target area as shown in the image. In other words, the silver iodide nuclei would be depleted through the nucleation process.

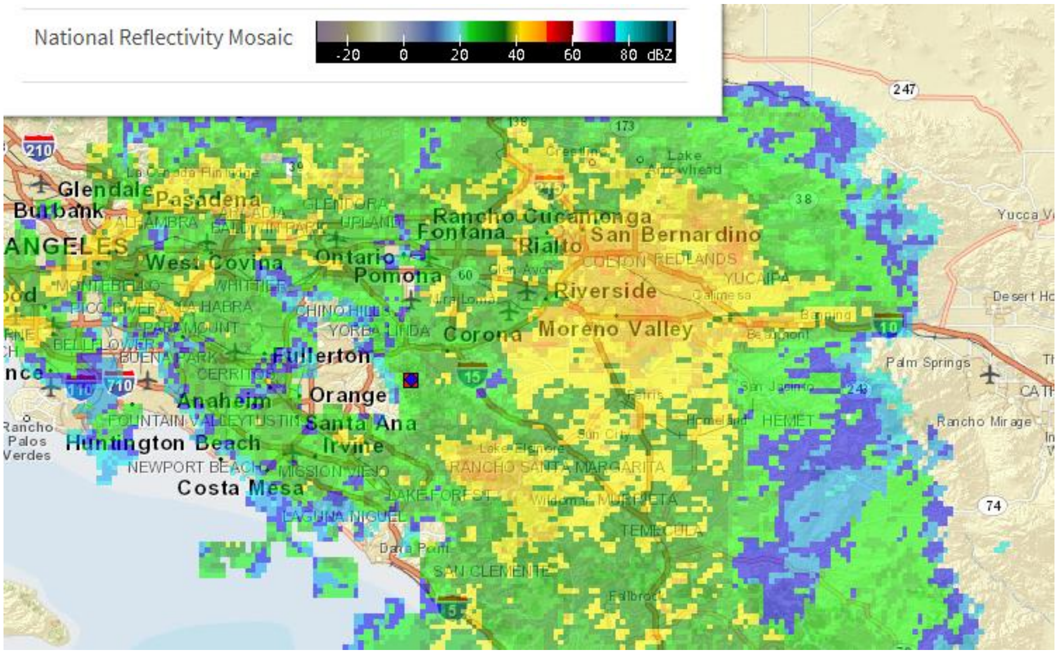


Figure 3.10. **NEXRAD Radar image from 1600 PST on January 9, 2018.**

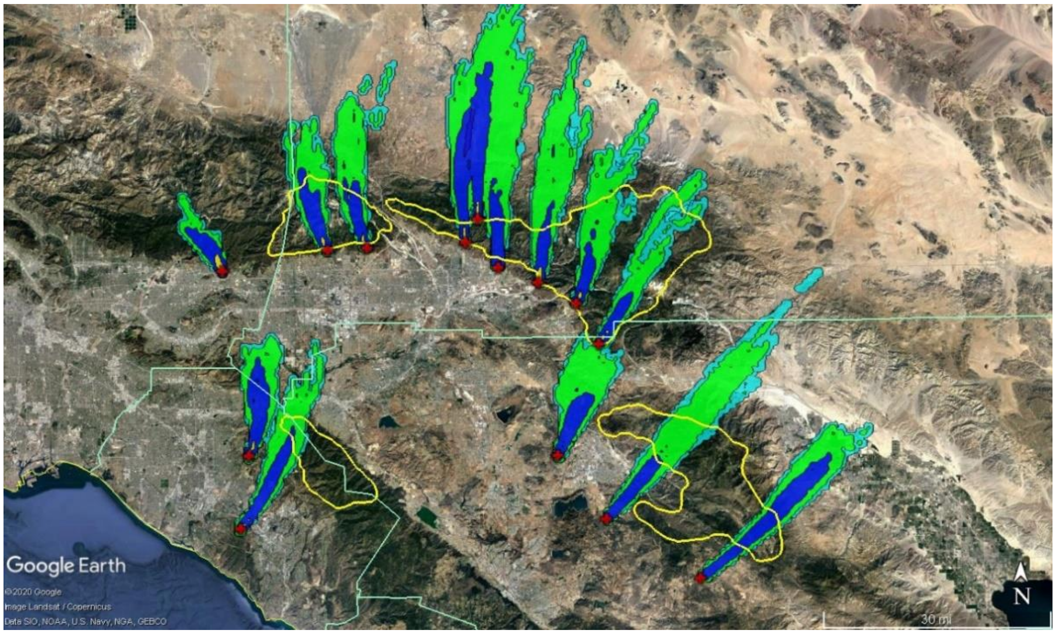


Figure 3.11. **HYSPLIT two-hour projected plume dispersion, valid at 1800 PST on January 9, 2018.**

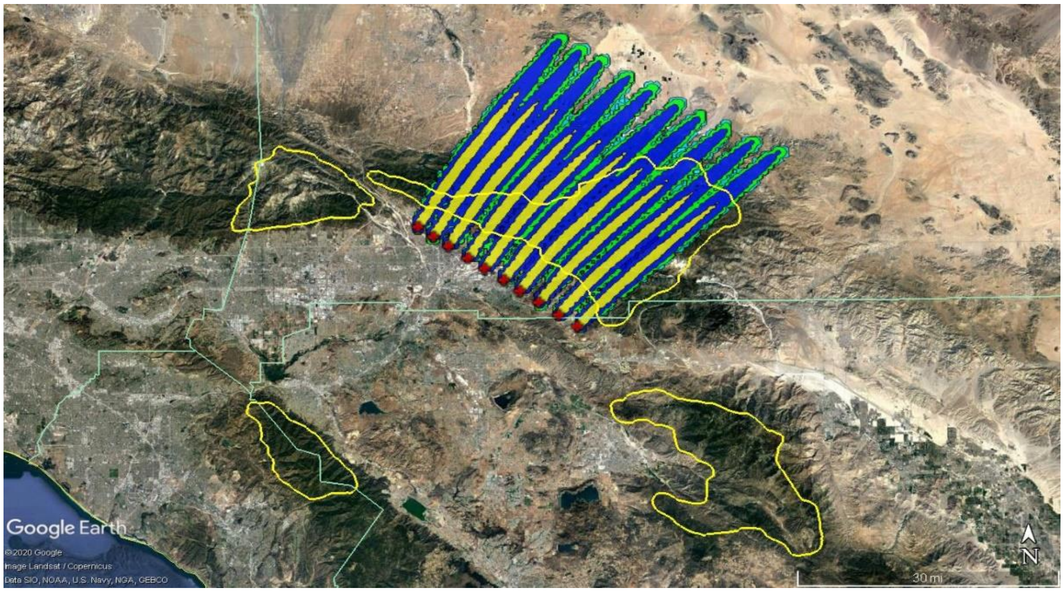


Figure 3.12. HYSPLIT one-hour plume dispersion from theoretical flight level (approximately 10,000 feet above sea level), valid at 1700 PST on January 9, 2018.

3.6 Operational Guidelines and Suspension Criteria

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 area NEXRAD radars, approach the ground sites.

For orographic storm conditions, seeding from ground generators primarily becomes a consideration of which ground sites should be activated and when they should be activated to properly result in seeding plumes passing over the target areas (i.e., correct targeting). The project meteorologist would make these decisions based upon upper-level wind flow observations and HYSPLIT modeling runs.

Sometimes "Atmospheric River" storms will impact the proposed target areas during the winter season. These storms are deep cloud systems fueled by tropical, or subtropical connections that can feed large amounts of atmospheric moisture into the werst coast including southern California. These storms produce high amounts of precipitation and are essentially naturally efficient in terms of precipitation production. In other words, cloud seeding would typically have no impact on such storms and consequently should not be seeded. Other reasons not to seed such systems include: 1) the likelihood of higher temperatures at the 700mb level which would render ground seeding ineffective and 2) concerns about flooding which could oftentimes invoke seeding suspension criteria. Experience has shown that seeding increases in wintertime are more likely to occur in light to moderate storms that are often less efficient in producing precipitation.

The proposed length of the seasonal winter cloud seeding program is for five months, November 15 – April 15th. This period would cover a significant majority of the natural winter season precipitation.

3.6.1 General Guidelines for Suspending Seeding Operations

One requirement in the design of all operational cloud seeding programs is to establish criteria that will determine when cloud seeding operations should be terminated if seeding is in progress or not initiated in other situations. Suspension criteria have been developed to minimize or avoid contributing to potentially hazardous situations.

Excessive rain or rain on top of snow can both result in heightened flood potentials. When a significant rain on snow event is expected, the forecast will be monitored closely to flag the potential for heavy rain or rain on snow. Coordination between the cloud seeding operator and water managers (or flood districts) will be appropriate in circumstances where the freezing level is > 7,000 feet and the Quantitative Precipitation Forecast (QPF) is > 3 inches in 24 hours.

The objective of suspension is to eliminate the real and/or perceived impact of weather modification when any increase in precipitation has the potential of creating or contributing to a significant flood hazard.

3.6.2 National Weather Service Bulletins

During periods of hazardous weather phenomena, associated with both winter orographic and convective precipitation systems, it is sometimes necessary or advisable for the National Weather Service (NWS) to issue special weather bulletins advising the public of the event. Each phenomenon is described in terms of criteria used by the NWS in issuing special weather bulletins. Those of concern in the conduct of winter cloud seeding programs include the following:

Winter Storm Warning:

Issued by the NWS when it expects heavy snow warning criteria to be met, along with strong winds/wind chill or freezing precipitation.

Flash Flood Warning:

Issued by the NWS when flash flooding is imminent or in progress, or a dam break is imminent or occurring.

Severe Thunderstorm Warning:

Issued by the NWS when a thunderstorm is expected to produce strong winds in excess of 58 mph or hail larger than one inch in diameter.

Seeding operations may be suspended whenever the NWS issues a Winter Storm Warning, a Flood/Flash Flood or Severe Thunderstorm Warning for or adjacent to any of the target areas. However, since an objective of the cloud seeding program is to increase winter snowfall in the mountainous areas where snow commonly falls, suspensions are not generally necessary when Winter Storm Warnings are issued, unless there are special, extenuating considerations, e.g., heavy snowfall to very low elevations or holiday periods.

Flash Flood Warnings are usually issued when intense convective activity causing heavy rainfall is expected, or when moderate rainfall is expected for extended periods. The types of storms that may cause problems are those that have the potential of producing 2-3 inches (or greater) of rainfall in approximately a 24-hour period, especially with high freezing levels (e.g., > 7,000 feet MSL). Seeding operations will potentially be suspended for the duration of the warning period in the affected areas when the 24-hour rainfall is forecast to be greater than 6 inches.

3.6.3 Specialized Considerations for the SW and SE Target Areas

In addition to these standard suspension criteria, additional criteria should be considered for areas of heightened risk.

The SW target area is of particular concern to NAWC. After a conversation with the Riverside County Flood Control and Water Conservation District, NAWC believes this area merits special consideration. The concern from the local flood district is not so much for the target area directly, rather the area of land downwind (north and east) of the intended target area. The concern is due, in large part, to underdeveloped infrastructure in this area leaving it particularly susceptible to flooding. It is not uncommon for flooding to inhibit transportation in and out of the area, leaving individuals unable to attend work or school. NAWC recommends implementing suspension criteria for this area based, not only on flood advisories, but also on precipitation forecasts. NAWC would suggest a suspension threshold (for this target area), between 0.5 and 0.7 inches in a one-hour period, or 2.0-3.0 inches in a 24-hr period. These values correlate to roughly a 1 in 2-5-year events, by magnitude.

Similarly, the generally dry soil of the SE target area (between Riverside and Palm Springs), would render this small range susceptible to flash flooding and heavy runoff. NAWC recommends a discussion between the Weather Modification contractor and the flood district if rainfall is expected to pass the thresholds selected for the SW target. This conversation may or may not result in a temporary hold on weather modification services, but it would ensure greater cooperation and transparency during times of heavy precipitation.

3.6.4 Wildfires

It is an unfortunate reality that the Transverse Ranges are no stranger to wildfires. After an event of significant scale, many flood districts worry about debris flow and runoff. In the past NAWC has worked with our California clients to determine the best response to fire related damages. Depending on the location of an event, the scale of the event and the extent of damages, it may be wise to cease operations for a time, a season or in some cases a multi-year period. The Santa Ana River Watershed is unique, in that it comprises four target areas, sufficiently divided and relatively easy to target individually. This would allow a weather modification contractor to target burn free areas of the watershed while avoiding burn scars, with relative ease. In the event of a fire NAWC recommends careful planning and deliberation between the Weather Modification Contractor and the SAWPA board to determine the best course of action.

3.6.5 Impact of Seeding Suspensions on Program Effectiveness

NAWC understands that suspension criterium are critical to the safety and positive public perception of a weather modification program. NAWC also understands that suspending seeding activity reduces the potential impact of the program. When the issues are weighed carefully it is possible to have a highly effective and very safe program. In determining when to recommend suspending operations NAWC addressed each of the four target areas differently, based on their locations, proximity to populations, infrastructure, propensity of flooding and probable down-wind affects. NAWC determined that the South West target area required special consideration, after carefully discussing the down-wind areas with the Riverside Flood Control District. In the end NAWC recommended elevated suspension criteria for this location. These criteria however, target the most severe of storm events, those most likely to overwhelm infrastructure and result in localized flooding or flash flooding. They are based on precipitation levels that typically only occur once every 2-3 years (a one in 2-year event). Probability would indicate that the contractor would only miss 1 event every two years due to flooding concerns, which would have only a marginal impact on the overall program effectiveness. In addition, the contractor would likely seed these events for the other 3 target areas during these storm events.

3.7 Weather Data

NAWC's project meteorologists are responsible for archiving relevant weather data (e.g. local NEXRAD radar displays, satellite photos and rainfall data) from each storm event. A variety of weather information is available via the internet that can be used to forecast approaching storms, forecast and observe weather conditions during storms as they pass through the area and document conditions of interest like criteria relating to suspension criteria. Some of these useful products include:

- Upper-air data, including important levels at 850, 700, 500, 300 and 250mb.
- Rawinsonde data: pressure, temperature and wind observations which are plotted (in the vertical) throughout the atmosphere.
- Radar and surface data which allow the meteorologists to view important parameters before and during seeding operations.
- Hourly observed precipitation data from ALERT networks in several counties in southern California, including streamflow data.
- Satellite imagery: visible, infrared, and water vapor presentations updated at intervals ranging from 5 minutes to one hour.

3.8 Operational Forecasting Models

A number of specialized forecasting models are expected to be used in the conduct of this program. These atmospheric models are of two basic types:

- Those that forecast a variety of weather parameters useful in the conduct of the cloud seeding program (e.g. WRF or HRRR)
- Those that predict the transport and diffusion of seeding materials (e.g., HYSPLIT).

3.8.1 Weather Research and Forecasting (WRF) Model

The Weather Research and Forecasting (WRF) Model is a mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. 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 including several agencies and universities. WRF provides operational forecasting via a model that is flexible and efficient computationally, while offering the advances in physics, mathematics, and data assimilation contributed by the research community.

3.8.2 High Resolution Rapid Refresh (HRRR) Model

NAWC utilizes NOAA's Earth Systems Research Laboratory's High-Resolution Rapid Refresh (HRRR) version of the WRF model. This model has a 3 km 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. 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 18 hours, such as composite reflectivity, total precipitation, 850 mb winds and temperatures, 700 mb winds and temperatures.

3.8.3 NOAA Aviation Weather Center Aircraft Icing Forecasts

Aircraft icing forecasts are produced that can be useful in inferring development of supercooled liquid water (SLW) at various levels (MSL up to 29,000 feet) in the atmosphere out to 18 hours. These forecast products are of particular interest because SLW is the substance targeted by silver iodide seeding for precipitation augmentation.

3.8.4 Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model

Accurate targeting of seeding releases is of great importance. In real time operations, the temperatures and winds can vary considerably from storm to storm and within storms. Given this large degree of natural variability, the task of the weather modification operator is to know where seeding should be conducted in each "seedable" storm event. Silver iodide typically does not become an active ice nucleating agent at temperatures warmer than about -5°C. Silver iodide becomes progressively more active at colder temperatures. Ice crystals created at -5°C will be of a different habit (shape) and grow at different rates than those created at -15°C. NAWC utilizes an atmospheric plume dispersion model developed by the National Oceanic and Atmospheric Administration (NOAA), known as HYSPLIT, for winter cloud seeding programs. The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model is a modeling system for computing simple air parcel trajectories to complex dispersion and deposition simulations. This model is used with operational model (e.g., GFS, NAM, HRRR) data to produce dispersion estimates for free-floating material released from a point source or sources. This can be of value in deciding if/when to seed in some situations, and in selecting which sites may provide good targeting of the seeding material.

3.9 Operations Plan

A detailed operations plan should be developed by the Contractor selected to implement this SAWPA cloud seeding program. This plan would be customized specifically for the intended target areas and would be available as a reference for all program personnel.

3.10 Environmental Considerations

Appendix E summarizes some past studies and reports that are concerned with the potential environmental impacts from precipitation augmentation programs. Appendix G summarizes issues related to long term climate change.

Should the SAWPA decide to implement a program based upon this feasibility study, a Mitigated Negative Declaration (MND) would need to be prepared and approved for the proposed program. MND's need to be prepared according to California Environmental Quality Act (CEQA) guidelines. NAWC has been involved in the preparation of similar MND’s for the Los Angeles County Department of Public Works, Sacramento Municipal Utility District, and the Santa Barbara County Water Agency operational cloud seeding programs.

3.11 Permits and Federal Reporting

California Department of Water Resources (DWR) Notification Requirements: State requirements for sponsors of weather modification projects consist of filing a notice of intent (NOI) initially, and every five years after for continuing projects; some record keeping by operators; and annual or biennial reports to the California Department of Water Resources (DWR). The information to include in the NOI can be obtained from DWR. In addition, sponsors need to comply with the California Environmental Quality Act and should send annual letter notices to the board of supervisors within affected counties and to DWR. The National Oceanic and Atmospheric Administration (NOAA) also requires activity reports, which give the number of days and hours of operation and the amounts of seeding material applied.

National Oceanic and Atmospheric Resources (NOAA): The National Oceanic and Atmospheric Administration (NOAA) under Public Law 92-205 requires the operators of cloud seeding programs conducted in the United States to file an initial, interim (if the project spans two calendar years) and final report for each seeded season. These are rather abbreviated forms that should be filed by the Contractor.

4.0 PROGRAM EFFECTIVENESS

4.1 Storm Period Meteorological Analyses

A total of 58 precipitation periods during five November – April seasons were analyzed to determine potential seeding increases in precipitation on a seasonal basis. These seasons were selected to include wet, dry and near average years that may be representative of the long-term climatology. The seasons include the 2010-11 season as well as 2014-15, 2015-16, 2016-17, and 2017-18. Significant precipitation periods were identified during those seasons and data were collected, including storm structure, precipitation type, vertical profiles of temperature, moisture, winds, and hourly precipitation for sites representative of each of the four target areas. Those sites with hourly precipitation data that were utilized in the analyses are shown in Figure 4.1.

These data were used to analyze each individual storm situation, including factors such as precipitating cloud types, any atmospheric thermodynamic stability, the height of the -5°C level (where cloud seeding becomes effective) and winds at the 700 mb (approximately 10,000 feet above sea level) and 850 mb (approximately 5,000 feet) levels as relevant to potential targeting of seeding material. Estimates of possible seeding effects were made for both ground-based seeding and aircraft seeding in each proposed target area for each of these cases. The results were compiled to generate estimated "average" seasonal increases (November – April) in precipitation with each seeding mode. Appendix A includes samples of the data used in these analyses.

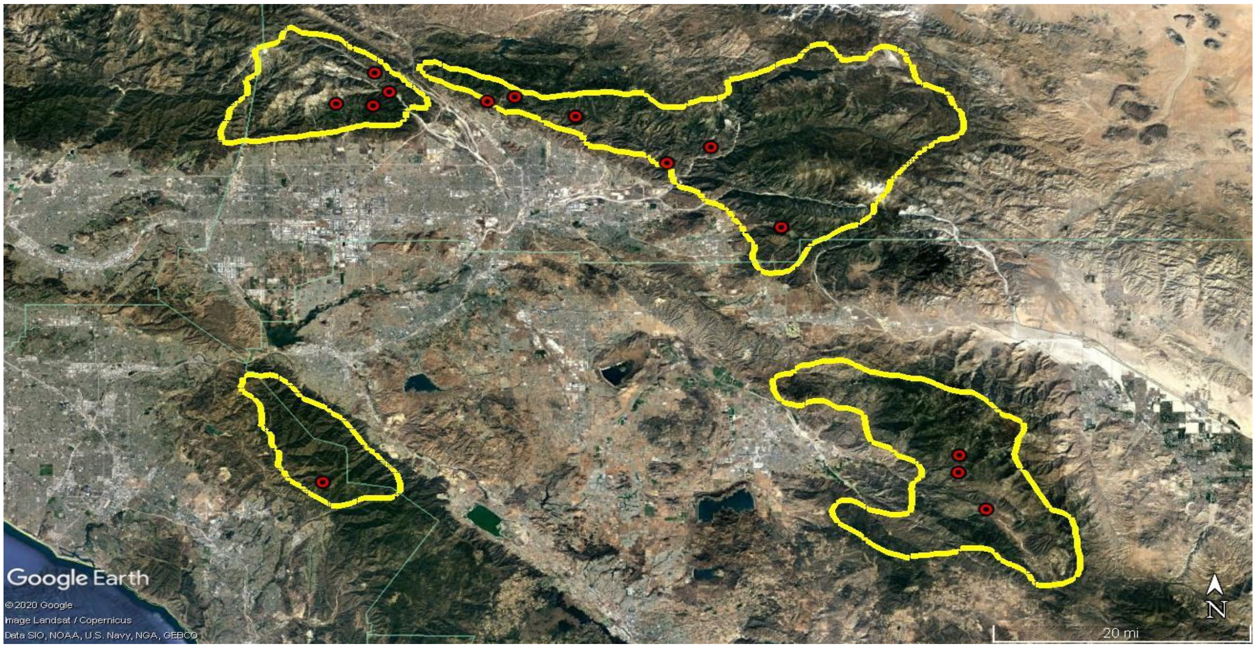


Figure 4.1. **Hourly rain gauge sites (shown as red circles) utilized in the storm period analyses. Yellow outlines define the four target areas.**

Several relevant issues were addressed in these analyses. These include the percentage of precipitation events that are classified as potentially seedable during a typical winter season, the frequency of events classified as distinct convective bands and the frequency/degree of thermodynamic stability below the -5°C level that may reduce the effectiveness of ground-based seeding.

When analyzing storm characteristics to understand the potential effectiveness of cloud seeding, there are a few attributes that are critical to consider. The first, is that silver iodide (AgI) does not exhibit strong glaciogenic effects until liquid water has cooled to around -5°C. The height of the -5°C level is therefore important, particularly for ground-based seeding operations in situations where the primary mode of air mass lifting is orographic rather than convective. This is because when the lifting mechanism is orographic, the height of a lifted air parcel is typically limited by the terrain height and its configuration relative to the wind field. Convective processes, on the other hand, can much more quickly lift an air parcel to significant altitudes where temperatures are much colder. This has important implications for the targeting of silver iodide, particularly from ground-based sites.

Cloud-top temperatures are an important factor, with some cases clearly having "warm" cloud tops where the top of the cloud is at an elevation below the -5°C level and thus are not considered to have glaciogenic seeding potential. Though cloud top temperatures are frequently difficult to determine and are typically highly variable with regards to both time and location during a given storm event, there were some clear-cut situations in these analyses where cloud tops were determined to be too low (warm) for effective seeding operations. Conversely, some research programs have shown that cloud seeding effectiveness typically becomes negligible in the -20°C to -25°C temperature range.

Analysis of wind direction during potential seeding periods was conducted and utilized in the development of a seeding site array for each potential target area. Airborne seeding was also included for the NE target area, in the analysis presented in this section. In reviewing both ground and airborne seeding, wind directions at the ground and aloft were considered. Models that can predict the dispersion of silver iodide into specific storm systems take into consideration varying speeds and directions.

For each target area, an array of precipitation sites with available hourly data were selected, with the objective of best representing the actual target area(s) precipitation amounts and patterns. These hourly precipitation totals were combined for the analyzed periods to obtain precipitation-weighted, target area-specific totals pertaining to the storm periods.

In the analysis of underlying seeding potential for each precipitation period, 11 of the 58 cases (19%) were determined to be not seedable by any mode due to overall storm characteristics, with the majority of these having low (warm) cloud tops, where all precipitation was apparently being produced below the -5°C level. A small subset of these cases involved only a higher cloud deck which produced only light stratiform precipitation and that are likely not seedable. An additional 12 cases (21%) were considered likely seedable by aircraft but not from ground-based sites, due to the -5°C level exceeding 700 mb (in stratiform cases) and/or a significant amount of thermodynamic stability (sometimes referred to by the term inversion) below the -5°C level which would trap the silver iodide nuclei below their threshold activation temperature. For this reason, while an overall 81% of the analyzed periods were theoretically seedable with aircraft, only 60% were judged to be seedable using ground-based sites.

There were a number of additional cases where a greater degree of seedability was assigned to aircraft than to ground-based sites due to a marginally high -5°C level and/or indications of minor stable layers below the -5°C level, although ground-based seeding was still considered to be viable in these cases. Overall, strong stability below the -5°C level that would prevent ground-based seeding operations was noted in only 10 of the 58 analyzed cases. Another 13 cases exhibited at least some minor stability that may potentially limit the vertical mixing from the surface up to this level but may not be a significant problem. To summarize, detailed analysis of 58 storm periods from five different winter seasons suggest that approximately 60% to 80% of those cases deemed seedable could be effectively seeded, with 60% seedable via ground-based seeding versus 80% seedable via aerial seeding.

Storm structure played an important role in the analyses and in the percentage of likely seeding increases attainable in each case. Based on previous studies of well-defined convective bands in coastal California, these situations were assigned the greatest overall potential with a likely 15% precipitation increase in ideal cases. However, distinct convective bands were a small minority of the precipitation periods identified, constituting only 10 of the 58 or about 17%. Frequently observed categories included scattered convective cells (generally assigned a 10% potential seeding increase), as well as situations with disorganized precipitation that typically involved a mixture of convective and stratiform precipitation types. These cases were generally assigned a 5% to 10% likely increase based on careful consideration of storm characteristics. Situations with distinct orographic (terrain-induced) precipitation, either stratiform or convective, were typically considered to have a 10% potential increase due to seeding. Situations involving widespread (non-orographic) stratiform precipitation, as well as other cases with some marginal parameters, were considered to have a 5% potential increase in precipitation.

The definition of distinct convective vs scattered convective cells is somewhat subjective. All of these were estimated, based on knowledge of the available literature and meteorological experience related to operational seeding programs both in California and other western states. As storm conditions are so variable, there is, unfortunately, no specific formula available to calculate specific percentage increases. An attempt was made to provide reasonable and somewhat conservative estimates that would pertain to an operational seeding program targeting these portions of the Santa Ana River Watershed. For comparison to our estimates in these cases, the Weather Modification Association 2016 capability statement suggests a seasonal range of increases from 5% to 15% in most winter cloud seeding programs.

Figure 4.2 shows some general categories of storm types and the rough proportion of total precipitation associated with each precipitation type, although these categorizations are admittedly somewhat subjective. The most precipitation by far was in situations labeled as "disorganized", which generally included a lot of larger events that were a mix of stratiform and convective precipitation but lacked any distinct frontal precipitation features. These proportions of total precipitation did vary somewhat between the different target areas.

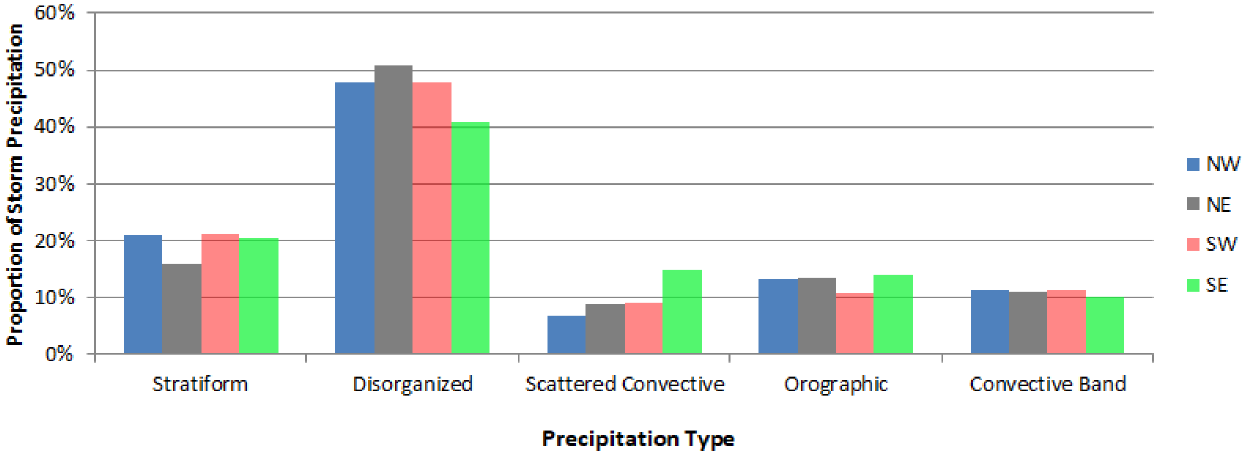


Figure 4.2. **Rough proportion of precipitation type in various types of storm situations, by target area.**

For the analyzed periods, 59 representative soundings (weather balloon observations) from the closest RAOB (official weather sounding) site, located in San Diego, were used to assess temperatures and winds. An example of a sounding is shown in Figure 4.3. These were selected as representative of periods judged to have some seeding potential based on other factors as described previously, with non-seedable (such as warm-cloud topped cases) excluded for this wind analysis. Some interpolation of the data was necessary, as sounding times were only available twice a day and a storm period could fall in between these during a storm period when synoptic and mesoscale conditions are changing quickly. The average 700 mb (millibar) temperature for these representative soundings was -3.5°C, which correlates with an average -5°C height of around 11,000 feet MSL or roughly 675 mb. This is quite high for ground-based seeding in stratiform situations, although most precipitation periods had at least some convective activity which could more quickly carry ground-based seeding plumes to elevations well above the terrain height (and thus likely to above the -5°C level). Therefore, ground-based seeding was judged to be viable for many of the warmer situations in the absence of any significant stable layers. The overall variation of 700 mb temperatures was from +4.0°C to -12.7°C. At 850 mb (about 5,000 feet MSL) the average temperature was +5.3°C, with an overall variation from +12.0°C to -2.3°C at this level.

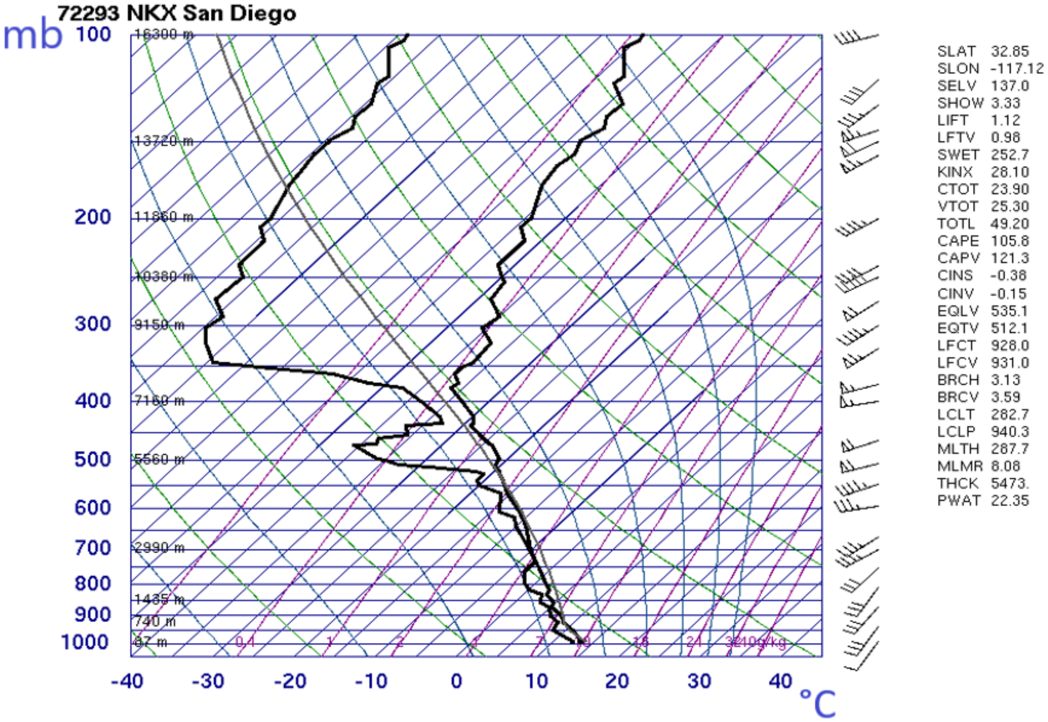


Figure 4.3. RAOB (weather balloon) sounding from San Diego at 00Z January 10, 2018; black lines are temperature and dew point, and barbs at right of the plot show winds.

Wind analysis for the 700 mb level showed an average wind direction from 236° (slightly west of due southwesterly, which is 225°). Wind directions varied from 135° (southeasterly) to 315° (northwesterly), distributed through the southerly/westerly sectors with 46 of the 59 or 78% between due southerly and due westerly (see wind rose plot in Figure 4.4). In interpreting the wind rose plots, meteorological convention is for wind directions to be reported in the direction from which the wind is blowing. For example, a southwest wind direction would indicate the wind is blowing from the southwest towards the northeast. A wind rose plot provides the frequency of different ranges of wind direction and wind speed. Only four cases were east of southerly at 700 mb, and nine were north of due westerly. Consequently, the winds at the 850 and 700 mb levels are primarily blowing from the southwest. This was an important finding in terms of selecting potential ground-based seeding sites, a topic discussed in Section 3.5. The average wind speed at 700 mb was 35 knots in these soundings, varying from 7 knots minimum to 67 knots maximum. There was an overall peak in the average wind speed at this level (over 40 knots) for cases where winds were southwesterly, or close to 235°. The average 700 mb temperature varied from about -1°C for due southerly periods (more southerly than about 210°) to roughly around -5°C for wind directions more westerly than about 240°.

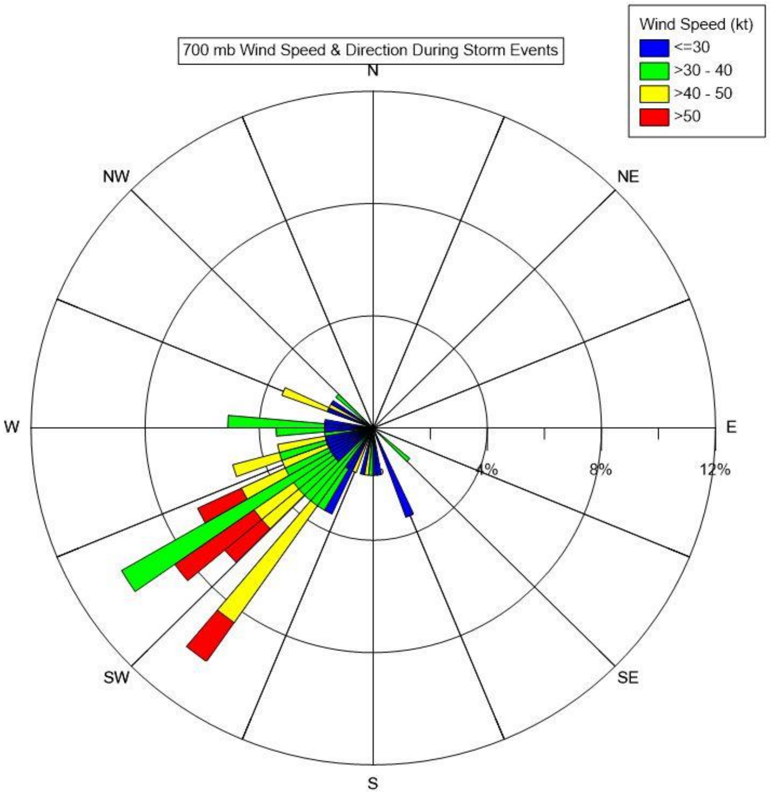


Figure 4.4. **Wind rose diagram showing 700 mb wind speed and direction frequencies for all 58 storm periods.**

While the 700 mb wind distribution may be more applicable to aircraft seeding in the vicinity of the -5°C level, the 850 mb (approximately 5,000 feet MSL) wind may be more applicable to the targeting of seeding material from ground-based sites. A similar analysis at this level showed a mean southwesterly wind direction from 231°, varying from 95° (southeasterly) to 305° (west-northwesterly), as seen in Figure 4.5. 76% of the soundings had 850 mb winds between due southerly and due westerly, with 5 to the left (east of south) and 9 to the right (north of westerly). The average wind speed was 24 knots at 850 mb, varying from 1 knot to 53 knots. At 850 mb, the wind speed did not show any clear relationship to wind direction. The 850 mb temperature average varied from about +8°C for southerly cases to around +3°C for westerly cases to the right of about 260°.

The temperature change with respect to wind direction is similar at both the 700 mb and 850 mb levels, implying that the westerly wind situations are roughly 5°C colder than southerly situations. This suggests a likely bias toward more favorable ground-based seeding conditions, particularly when winds are more westerly in direction. Meteorologically, more westerly winds are typically associated with an upper-level trough axis closer to the area, resulting in colder temperatures aloft. Although the bulk of the precipitation with an event frequently occurs in pre-frontal conditions associated with more southerly winds, a higher -5°C level can make ground-based seeding somewhat more challenging in those situations. Figures 4.6 and 4.7 are wind roses showing the distribution of winds and temperatures during the storm periods, at 700 mb and 850 mb, respectively.

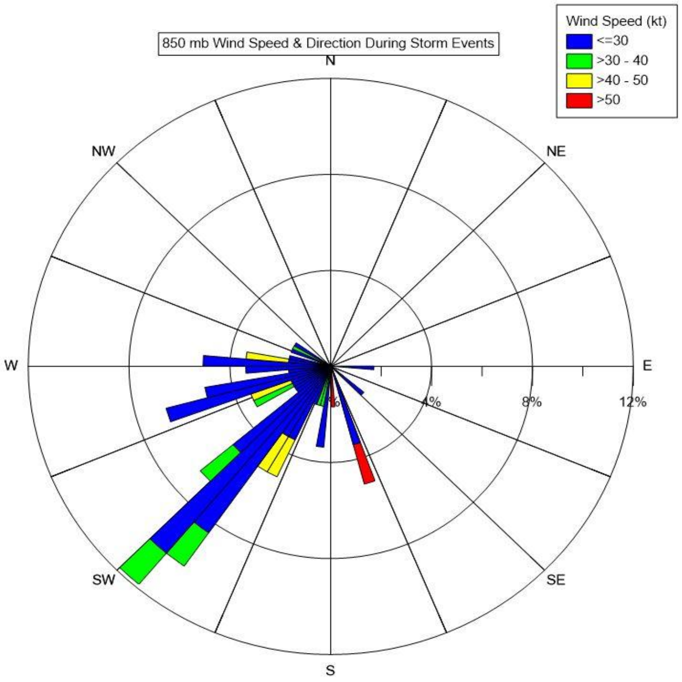


Figure 4.5. **Wind rose diagram showing 850 mb wind speed and direction frequencies for all 58 storm periods.**

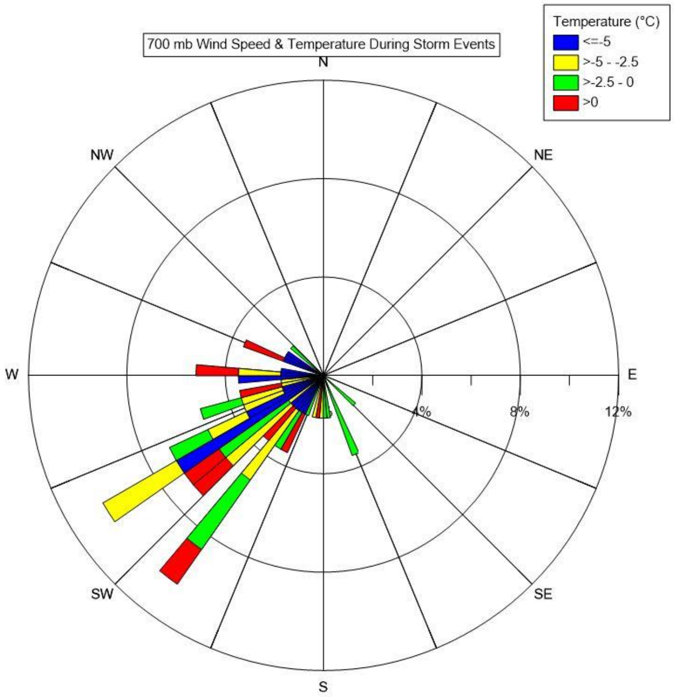


Figure 4.6. **Wind rose diagram showing distribution of 700 mb winds and their corresponding temperature frequencies (color shading) for all 58 storm periods.**

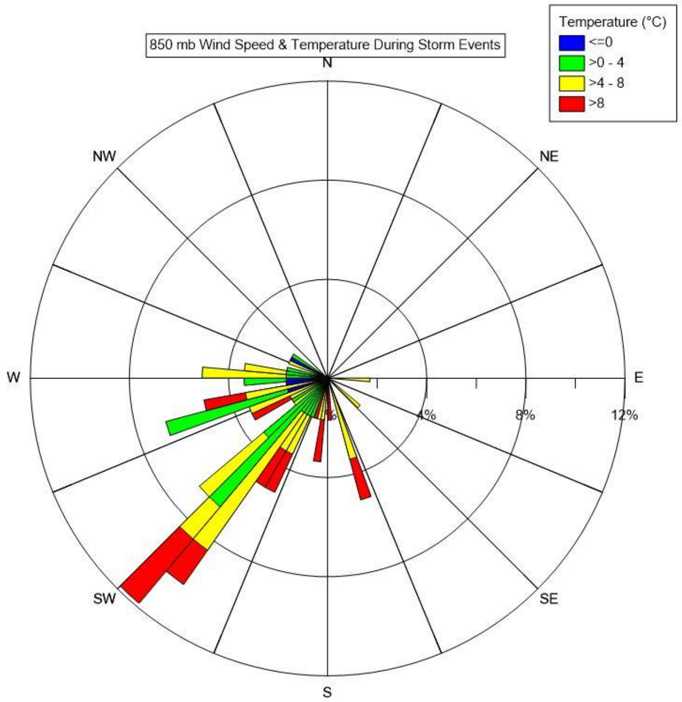


Figure 4.7. **Wind rose diagram showing distribution of 850 mb winds and their corresponding temperature frequencies (color shading) for all 58 storm periods.**

4.2 Estimates of Potential Seeding Increases in Precipitation

Compiling the data and resulting seedability estimates for each of the storm periods in the five-season analysis allows a precipitation-weighted estimate of an average seasonal increase for each target area. Due to differences in precipitation patterns with respect to geography of these areas, the total estimated seeding increases differ somewhat. For the NW target area, an estimated seasonal (November – April) precipitation increase of 3.5% due to ground-based seeding was obtained in this analysis. For the NE target area, an estimated precipitation increase of 4.1% for ground-based seeding and 7.3% for ground and aircraft seeding operating in tandem was obtained. This is the only area where aircraft seeding was included in the analysis. For the SW target area, an estimated seasonal precipitation increase of 3.7% was indicated for ground-based seeding. For the SE target area, the estimate for ground-based seeding increase was 4.5%. These estimates may be somewhat conservative, but they are useful for pairing with the precipitation/streamflow relationships to obtain rough estimates of total streamflow increases that are likely from a cloud seeding program of this type. These estimates are presented in Table 4.1 in Section 4.4.

The total estimated seeding increases in precipitation for these analyzed storm periods, examined with respect to winds at the 700 and 850 mb levels, showed that most of the increases were associated with winds between southerly and westerly. Figures 4.8 and 4.9 show the distribution of the estimated increases with respect to wind direction at these two levels. Almost none of the estimated seeding increases in precipitation for these cases were associated with winds east of southerly at these two levels; however, it was observed that roughly 10-15% of the estimated increases, that is, the total potential benefit due to seeding, were associated with winds in the WNW sector (between 270-300 degrees) at the 700 and 850 mb levels. This result varied somewhat between target areas, although in the cases of deeper WNW flow (i.e., that seen at the 700 mb level), significant differences were noted between target areas. The NW target area in particular had the least amount of seeding increase associated with this WNW wind sector (only 8% of its total) and the SE target area had the highest corresponding proportion (nearly 18% of its total) in this 700 mb wind sector. Given the topography, the expected shadowing of the NW target area by adjacent terrain to the west and likely channeling of air through the LA/Riverside basin areas toward the SE target area with winds in this sector, these results appear to make sense.

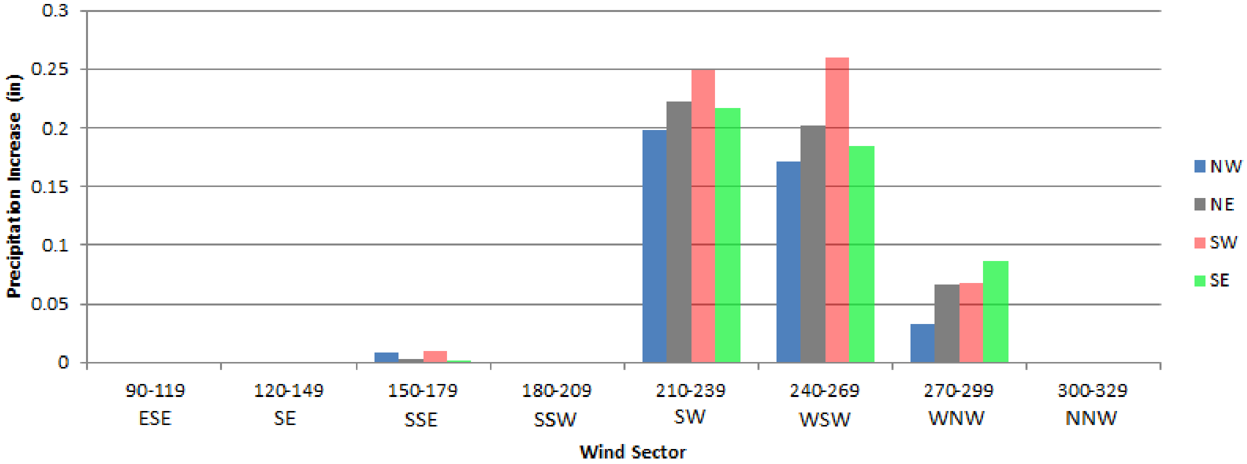


Figure 4.8. **Estimated (annualized) precipitation increases from seeding, by 700 mb wind direction.**

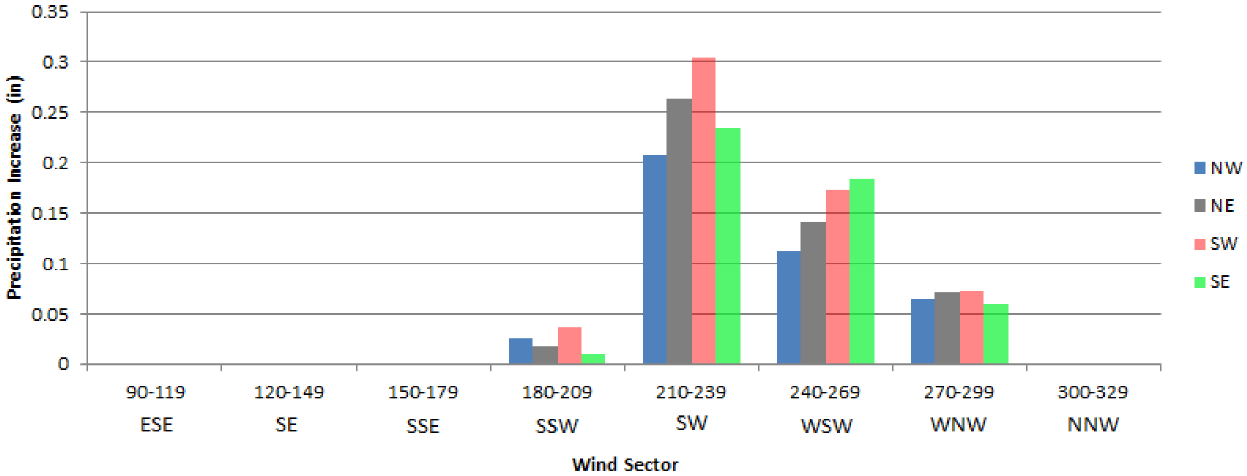


Figure 4.9. **Estimated (annualized) precipitation increases from seeding, by 850-mb wind direction.**

4.3 Development of Precipitation/Streamflow Regressions

Estimates of streamflow based on long-term data from USGS and other sources suggest the following long-term “average” annual runoff for the various potential target areas: NW target area: 25,000 AF; NE target area: 65,000 AF; SE target area: 10,000 AF; and SW target area: 5,000 AF. These target areas were identified in Figure 1.1. The two southern areas have highly variable runoff from one year to another and may generate little to no runoff during some years. It is important to note that, based on a review of the topography of the various target areas and the available stream gauge data, NAWC believes there may be significant amounts of runoff that are not included in the above estimates since some tributaries may not have stream gauging sites.

Regression equations were developed between precipitation and streamflow based on long-term data sets from various time periods, some beginning as early as the 1920s. Appendix A contains samples of these regression analyses, which will all be available as separate files in support of the final results of the study. Figures 4.10 and 4.11 show the long-term precipitation and stream gauge sites utilized in this portion of the analysis, and Appendix B contains coordinates for each of these sites. As a whole, the precipitation/streamflow regressions suggest that the best and most representative correlations relevant to this study are between November – April total precipitation and the annual (November – October) runoff. The data sets were utilized in this way for the precipitation/streamflow regression calculations. However, the results using various seasonal periods appear similar in terms of the increases in runoff as a result of increased precipitation, with nearly all of the annual streamflow generated by November – April precipitation. It should also be noted that, although some of the precipitation data sets involve sites that are no longer active (and in fact, a few of these stopped collecting data decades ago), there was no bias evident in the results of these regression when using different historical periods. In fact, good to excellent correlations between precipitation and streamflow, as well as consistency regarding the results for a given geographic area, were generally observed. Results of these regressions are summarized for the various seeding target areas under consideration, using the estimated increases to seasonal (November - April) precipitation derived from the storm period analyses (Section 4.2).

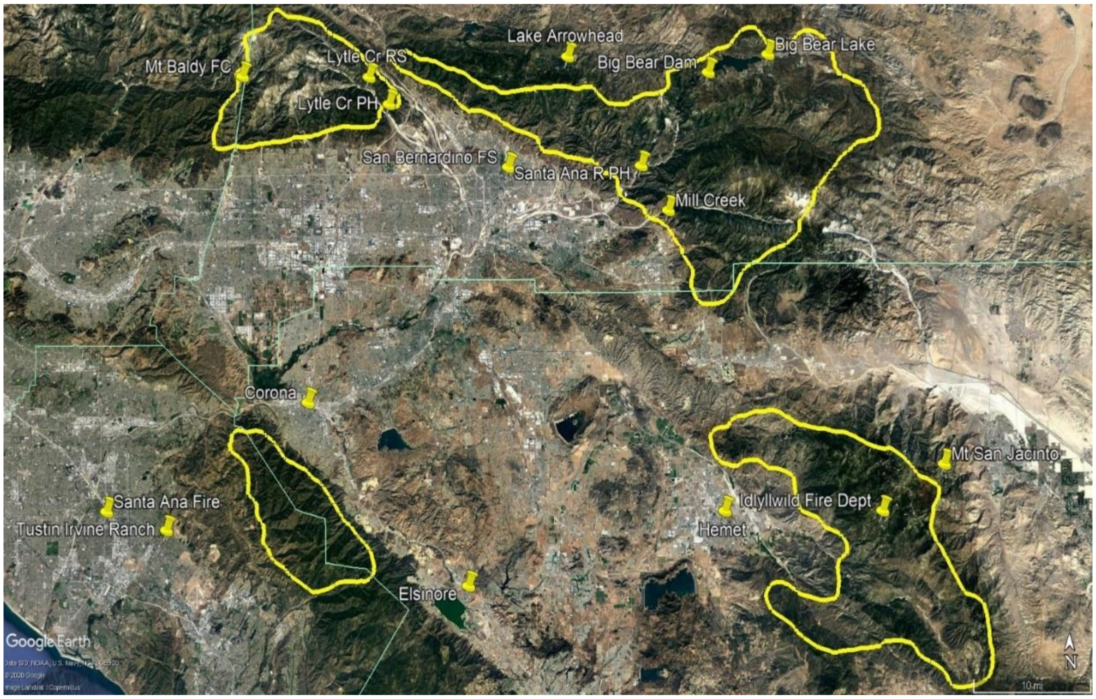


Figure 4.10. **Sites with long-term monthly precipitation data in and near the target areas.**

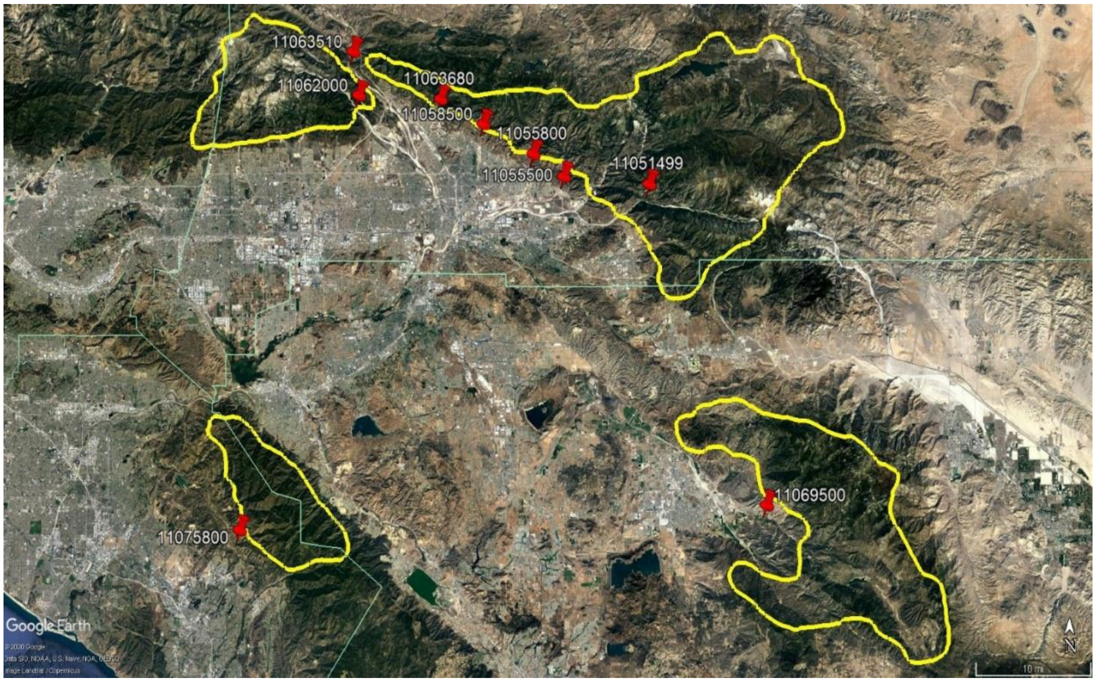


Figure 4.11. Stream gauges utilized in the precipitation/streamflow regressions.

For the NW target area, correlations between Lytle Creek streamflow and the best correlated precipitation gauges in or near the target area resulted in R values around 0.85 (Mount Baldy FS and Lytle Creek RS). These precipitation gauges did not have current data, but a long period with good records for both precipitation and streamflow (back to about the 1930s) was available for analysis. A regression for a nearby gauge at Cajon Creek below Lone Pine (averaging close to 8,000 AF annual flow during its period of record) was only possible using the Lytle Creek RS precipitation gauge, for which significant overlap of the historical data period with this station is available. An R value of 0.91 was obtained indicating excellent correlation using this gauge. A long-term annual average natural runoff base value is estimated at about 25,000 AF for the NW target area.

For the NE target area, regressions for several tributaries were developed. For Devil Canyon streamflow, good correlations (R values in the 0.73 to 0.85 range) were obtained with San Bernardino Fire Station, Lake Arrowhead, and Lytle Creek RS precipitation stations. Good correlations were also developed between the San Bernardino FS precipitation gauge and streamflow in East Twin Creek, City Creek, and Plunge Creek (corresponding R values were between 0.80 and 0.90). A very long precipitation record at the San Bernardino FS site resulted in long periods (from 50 to 80+ years) of corresponding data from which to develop these regressions. For the Santa Ana River gauge near Mentone, a good correlation was obtained with the San Bernardino FS precipitation data (R value of 0.76). However, this Santa Ana River stream gauge, which measures by far the largest portion of the streamflow originating in the NE target area, is better correlated with precipitation in the Big Bear Lake area. A precipitation gauge at Big Bear Lake provided the best correlation (R value of 0.82) with the main stem of the Santa Ana River. The equations developed using well-correlated data (e.g., precipitation and streamflow) were quite consistent, regardless of the historical time period involved. The NE target area has a much higher long-term annual average natural runoff value than for all the other areas combined, with an estimate of approximately 65,000 AF.

For the SE target area, the San Jacinto River near San Jacinto was well correlated with a couple of the precipitation sites. Regressions for those sites with long precipitation records and good correlation (Idyllwild Fire Dept and Hemet) had R values for these regressions of 0.84 and 0.79, respectively. A site called Mount San Jacinto, with a very short precipitation record of less than 10 years in length collected during the 1970s, had a very high correlation to the San Jacinto River gauge (R value of 0.94) for this short period; however, this period of record is considered too short to provide a truly reliable regression. A long-term annual average of 10,000 AF of natural runoff is the base value estimate for the SE target area.

For the SW target area, several precipitation sites with reasonable overlap periods to Santiago Creek were found: Elsinore, Corona, Tustin Irvine Ranch, and Santa Ana Fire Station. Correlations in all these regressions were good, with R values between 0.82 and 0.91. The Santa Ana FS, having a very long precipitation record that provided a regression period of 57 years with Santiago Creek, was used as the primary site for determining the precipitation/streamflow relationship for this area. A long-term annual average of 5,000 AF of natural runoff is the base value used for the SW target area, based largely on the runoff in Santiago Creek.

It should be noted that the estimates of average annual runoff for the four target areas may be on the conservative side since it is likely that not all tributaries from these areas have stream gauges to observe streamflow.

4.4 Increased Runoff Estimates

For each target area, the storm period seedability estimates (as described in Section 4.2) can be utilized in the long-term precipitation/streamflow regressions as described above, for the various tributaries fed by these watersheds. These yield estimates for increases in total annual runoff (expressed in acre-feet) were derived from estimates of the increase in November - April precipitation due to potential cloud seeding operations. The estimates for annual streamflow increase were in turn used to calculate preliminary benefit/cost ratios for each of the four geographical (target) areas, as well as for each seeding mode being considered. These costs and benefit/cost ratios are discussed in Section 5. Appendix A contains information on the precipitation and streamflow regression equations.

For the NW target area, a composite 3.5% November – April precipitation increase was applied to long-term regressions for Lytle Creek and Cajon Creek. Resulting increases in annual streamflow calculated by this regression were 10.8% (1,725 AF) for Lytle Creek and 4.5% (318 AF) for Cajon Creek. In total, an estimated **2,043 AF** increase to annual runoff was obtained for this area, which can be applied to an annual average base runoff value of approximately 25,000 AF, which is roughly an estimated 8.2% increase.

For the NE target area, estimated precipitation increases for both ground-based and aircraft seeding were produced for several tributaries. Composite seasonal precipitation increases of 4.1% (ground-based) and 7.3% (aircraft) were applied to runoff from Devil Canyon, East Twin Creek, City Creek, Plunge Creek, and the main stem Santa Ana River near Mentone. For ground-based seeding, the total estimated increase in runoff obtained for all these tributaries was **4,330 AF**, which (applied to a base annual runoff value of 65,000 AF for the target area) is an estimated total increase of 6.7%. With the addition of aircraft seeding, a total of **7,772 AF** is projected, which, when applied to the same base value of 65,000 AF is an estimated total increase of about 12.0%. **It should be noted in this analysis of dual seeding modes that aircraft seeding is considered to be the total increase attainable with ground and aircraft operating in tandem.**

For the SW target area, an estimated 3.7% precipitation increase due to ground-based seeding was applied to the regression for Santiago Creek. This results in an estimated increase of **447 AF** of runoff for a typical season, or around a 9% increase. The natural base value of runoff for this target area was estimated to be about 5,000 AF in a typical year, roughly represented by that contained in Santiago Creek. However, it should be emphasized that runoff for this area is somewhat uncertain, and there have been suggestions that some of it may be contributing mainly to groundwater recharge rather than surface runoff. Also, runoff in this area is highly variable on an annual/seasonal basis, such that the runoff may be essentially zero in some dry seasons, and thus a seeding program may not achieve an obvious benefit in certain dry years for this particular target area. As will be discuss in more detail in later portions of the feasibility study, for this reason, this target area would not be considered feasible as a stand-alone program.

For the SE target area, an estimated 4.5% precipitation increase due to ground-based seeding was applied to the regression for the San Jacinto River gauge near San Jacinto. The precipitation percentage increase was a bit higher for this area, likely due to a greater proportion of precipitation occurring in the somewhat colder, more westerly wind situations that are typically more conducive to ground-based seeding. Two regressions (using both Hemet and Idyllwild Fire Department precipitation sites) were similar in terms of historical period of record. The results using Hemet are somewhat more conservative and indicate an estimated increase of **1,373 AF** of runoff for a typical season. An average annual base flow estimate used for this target area as a whole is around 10,000 AF. Based on this, an increase of 1,373 AF represents an increase of 13.7% in streamflow. Considering that the more conservative result of the two regression equations was used, this is believed to be a reasonable increase achievable due to seeding for this area even when using a somewhat lower base flow value. However, like the SW target area, runoff in this region is highly variable from year to year, with total natural runoff of less than 1,000 AF indicated by the San Jacinto River gauge for several dry years. This high variability increases the uncertainty of runoff increase estimates for this area, especially percentagewise. As with the SW target area, this variability, and its impact on economic feasibility will be addressed in greater detail in later stages of the feasibility study.

Table 4.1 shows estimated precipitation increases and resulting streamflow increases for each of the target areas under consideration. For the NE target area, estimates for ground-based and aircraft seeding are shown separately. Figure 4.12 summarizes the results for each target area.

Table 4.1

Estimated Precipitation and Streamflow Increases

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

TOTAL w/ Ground and Air	**105,000**	**11,635**	**11.1%**

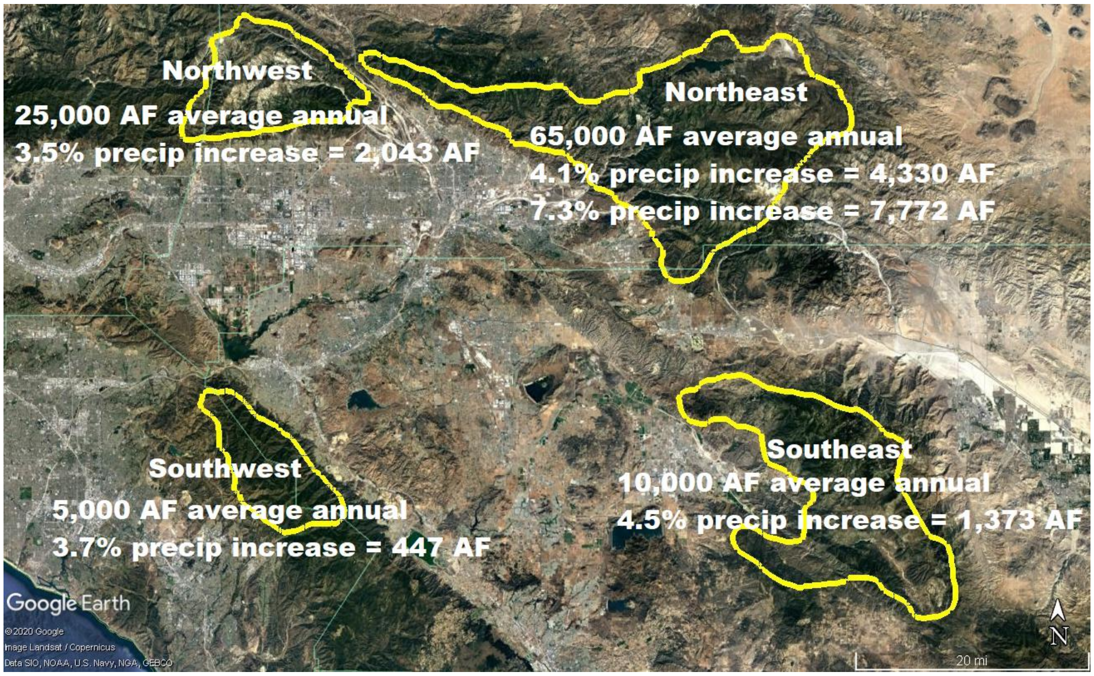


Figure 4.12. Map of target areas with precipitation and streamflow increase estimates.

It should be noted that, given the high year to year variability in southern California's precipitation patterns, the potential impacts of cloud seeding are likely to be quite variable from one season to another as well. Appendix C discusses the potential magnitude of this variability in terms of additional runoff generated in wet vs. dry years, using various precipitation/streamflow regression techniques. The comparison of wet to dry years in this context involves complex hydrological issues that are somewhat beyond the scope of this study, but it highlights some important considerations that may be relevant to the conduct of a seeding program and to general water management decisions.

4.5 Program Evaluation

The task of determining the effects of cloud seeding has received considerable attention. Evaluating the results of a cloud seeding program for a single season is typically difficult, and any such single-season results for an operational seeding program should be viewed with appropriate caution. This difficulty is due to the large natural variability in the precipitation occurring in a local area from season to season, and variations in precipitation patterns in the larger region during a given season. If the increases in precipitation due to cloud seeding are relatively modest, percentage-wise, it normally takes a number of years to document the effects on a particular program with a high level of confidence (typically 5-10 years is preferred). Since cloud seeding is feasible only when existing clouds are near to, or already are producing precipitation, it is not obvious if and how much the precipitation was actually increased by seeding in any particular storm event. The target/control technique is originally described by Dennis (1980) and is the basic technique that NAWC uses to evaluate operational programs.

The ability to detect a seeding effect is a function of the magnitude of the seeding increase and the number of seeded events, compared with the natural variability in the precipitation pattern. Larger seeding effects can be detected more readily and with a smaller number of seeded cases than are required to detect smaller increases. Despite the difficulties involved, some techniques are available for evaluation of the effects of operational seeding programs. The most scientifically rigorous evaluation process relies on a randomization technique, where about half the "seedable" storm events are randomly left unseeded and then compared to the seeded areas. This is the preferred method for core research programs (e.g., the Santa Barbara II research program referenced earlier), however, most sponsors of operational cloud seeding programs do not wish to reduce the potential benefits of a cloud seeding program by half in order to better document the effects of their cloud seeding project.

NAWC develops and employs a less invasive "target/control" analysis to evaluate its operational cloud seeding programs (e.g., Griffith et al., 2009; Griffith et al., 2011). This technique is based on selection of a variable that would be affected by seeding, such as precipitation or snow water content. Records of the variable to be tested are acquired for a historical period of many years. These records are partitioned into those located within the designated "target" area of the weather modification project and those in designated "control" areas. Ideally, the control sites should be selected in areas meteorologically and topographically similar to the target area but unaffected by the seeding or seeding from any other nearby projects. The historical data (e.g., precipitation and/or snow water content) for both the target and control areas are compiled for years during which no cloud seeding activities occurred. These data are then used to develop linear or sometimes multiple-linear regression equations that can be used to predict the amount of target area precipitation, based on observed precipitation in the control area. When the regression is then applied to a period when the target area is seeded, it can be used to predict what the precipitation should have been had seeding not occurred.

This comparison between the predicted seasonal target area precipitation and the actual observed precipitation that occurred during the seeded period is then averaged for multiple years of seeding. Typically, the observed precipitation amounts are divided by the predicted amounts. If this ratio is greater than 1.0, there is an indication of more precipitation in the target area than that predicted from the control area precipitation, possibly indicative of a seeding effect.

The four target areas for the SAWPA program are those described in Section 1.4. Control sites outside the target areas are similarly selected based on data quality and period of record, as well as by their degrees of correlation to the target area sites. The control sites are usually upwind or adjacent to the target areas, in regions that are considered free of any seeding impacts. It is possible to use the same set of control sites for all the target areas, or to have different selections of control sites that are best suited to each individual target area. The types of data used as target and control variables in these equations can include seasonal precipitation totals, snowpack (where applicable), and sometimes streamflow data. The goal in developing the equations is to obtain an accurate picture of the effects of the seeding program over the longer term, while minimizing background noise that is due to natural variability in weather patterns, as well as measurement deficiencies and other factors.

There are two basic types of regression equations that are typically used in these evaluations: linear regression, which uses two variables – one target and one control, and a multiple linear regression which considers each control variable separately. For the linear regression, a target site average and control site average at the two variables used if there are more than one site in each set. For the multiple linear regression, the target sites are also averaged, although this equation contains a separate coefficient for each control set. Sometimes groups of control sites may be average for a multiple regression as well. In any case, the multiple regression provides a similar, yet somewhat different, mathematical basis for evaluation of the seeding program. Using various types of equations in this way, as well as different types of data can provide greater confidence in the obtained results than from one equation alone. This assumes, of course, that there is reasonable agreement among the various results that are obtained.

In the case of the SAWPA program, very long precipitation records are available from some sites in the target areas. A number of these may be suitable as target sites in a target/control evaluation, and ideally correlated with precipitation records of similar length at sites outside the target areas. Also, streamflow data from the target areas could be used as a target variable, correlated against either streamflow or precipitation records outside the target areas. As cloud seeding is becoming more and more common in Southern California, it is difficult to designate specific control site(s) at this time, not knowing if that area will be incorporated into a future seeding program, before the first evaluation would be completed. NAWC can, however, provide a few examples of possible control sites, some of which have been utilized for evaluation of other seeding programs in this area. These include the LA Civic center (good precipitation records back to before 1920), Ojai (records back to the mid-1920s), Palomar Mountain Observatory (records back to the 1980s), and the Los Angeles Airport (records back to the mid-1940s). Should a cloud seeding program be desired in response to this feasibility report, the selected contractor should, ideally provide an evaluation method for the program prior to the commencement of seeding operations.

5.0 TECHNICAL AND ECONOMIC FEASIBILITY

The ASCE 2016 "Guidelines for Cloud Seeding to Augment Precipitation" publication states that for a proposed precipitation augmentation cloud seeding program to be feasible it needs to be both technically and economically feasible as determined in a feasibility study prior to the initiation of a program.

5.1 Technical Feasibility

The following is taken from the RFP under the sub-heading Technical Feasibility: "In this criterion, scientific data is considered as a basis for determining whether the proposed work could yield the desired additional precipitation."

The technical feasibility of the proposed SAWPA program has been examined in previous sections of this report. Specifically, the program design summarizes why the program is considered technically feasible based upon the results obtained from previous relevant winter research and operational cloud seeding programs (i.e., scientific data). From the work performed for all previous tasks, NAWC concludes that a program, following the proposed design specified, is technically feasible.

5.2 Economic Feasibility

According to the ASCE 2016 publication, the best method for determining the economic feasibility of a proposed program is to perform a benefit/cost analysis. This portion of the study considers the financial interests of the public, benefiting agencies, as well as individual SAWPA member districts.

For the purpose of budgetary considerations, NAWC will use the program design as outlined in this study (Section 3). It is important to note that this design is preliminary, the actual program design will be determined through the RFP process and by the ultimate selection of a Cloud Seeding Operator. During the RFP process, SAWPA will receive program designs from each participant that may differ significantly in certain design elements. These different designs should be considered carefully.

Program designs for weather modification vary from simple designs, focusing on a relatively small target area, to significantly more complex programs. A critical step in evaluating a potential target area is determining the lowest level of complexity with an acceptable benefit/cost ratio necessary to achieve the desired results. As will be made apparent in the review of projected program expenses, there is a point of diminishing returns, where program complexity may eventually drive the costs of operations above the value of the augmented runoff or yield a low benefit/cost ratio. In addition, complex program designs may be difficult to administer and to operate.

The ASCE 2016 "Guidelines for Cloud Seeding to Augment Precipitation (Chapter 6)" recommend a minimum benefit to cost ratio of 5:1 to justify economic feasibility. This accounts for the natural meteorological variability that will alter program success from year to year. This ratio represents the minimum viable benefit to cost ratio, NAWC believes program operators should strive to deliver closer to a 10:1 benefit to cost ratio in their program design, particularly in areas where seasonal seeding effectiveness is highly variable. This additional buffer helps ensure that the program will be productive even in years of relatively low storm occurrence.

5.3 Pricing Estimates

The following costs are provided only as estimates. Actual costs bid by potential contractors through an RFP process may be influenced by variable factors such as overhead rates, proposed seeding modes, the cost of silver and current rates for aviation insurance. Due to these and other factors, NAWC reserves the right to alter its economic proposal during the RFP phase, if NAWC is selected to participate in the bid process.

NAWC's cloud seeding program contracts consist of two forms of billings, fixed costs and variable costs. The fixed costs represent all predictable expenses. This includes, but is not limited to: equipment, personnel, travel, licensing and insurance. The variable costs are representative of the weather dependent materials, including ground-based generators (CNGs) burn time, flight time and silver iodide flare consumption (as discussed previously, flares are used with NAWC's Automated High Output Ground Seeding [AHOGS] systems as well as on wing-based flare racks for aerial seeding). Different contractors may utilize different billing structures, but most contractors involved in conducting operational cloud seeding programs will follow this general framework.

In order to calculate the benefit to cost ratio for this proposed program, SAWPA provided NAWC several estimates for untreated and unpressurized imported water resulting in an average calculated watershed wide value of $255 per acre-foot. This number was derived from conversations with numerous SAWPA member agencies, including the Orange County Water District and the San Bernardino Valley Municipal Water District. The Memorandum Report contained estimates of the increases in precipitation and streamflow. This information is summarized in Table 5-1. Tables 5-2 and 5-3 provide cost estimates and related information (e.g., benefit/cost ratios) for different cloud seeding modes. For the purpose of this report NAWC is assuming a five-month operational period (November 15th – April 15th). Aerial seeding is only proposed to impact the Northeast target area.

Table 5-1

Estimated Increases in Precipitation and Streamflow

Area	Precipitation % Increase	Streamflow % Increase	Streamflow Acre-Feet Increase
NW	3.5	8.2	2043
NE (ground)	4.1	6.7	4330
NE (aerial)	3.2	5.3	3442
SW	3.7	9.0	447
SE	4.5	17.0	1373

Table 5-2

Ground only seeding program, seeding all four target areas.

	Rate	Frequency	
Annual Operations			
Set Up	$ 33,500	1	$ 33,500
Take Down	$ 24,000	1	$ 24,000
Reporting	$ 10,000	1	$ 10,000
Monthly Operations			
Fixed Services	$ 24,500	5	$ 122,500
Variable Items (timed expenses are billed on a per hour basis)			
Ground Flares	$ 110	60	$ 6,600
Generator Run Time	$ 19.50	600	$ 11,700
Flight Time	$ 375	N/A	-
Aerial Flares	$ 110	N/A	-
		TOTAL	**$ 208,300**
		COST PER ACRE-FOOT	**$ 25.42**
		Benefit to Cost	**10.03**

Table 5-3

Ground seeding in all four target areas with aerial seeding in the North East target area.

	Rate	Frequency	
Annual Operations			
Set Up	$ 40,000	1	$ 40,000
Take Down	$ 31,000	1	$ 31,000
Reporting	$ 10,000	1	$ 10,000
Monthly Operations			
Fixed Services	$ 55,000	5	$ 275,000
Variable Items (timed expenses are billed on a per hour basis)			
Ground Flares	$ 110	60	$ 6,600
Generator Run Time	$ 19.50	600	$ 11,700
Flight Time	$ 375	30	$ 11,250
Aerial Flares	$ 110	150	$ 16,500
		TOTAL	**$ 402,050**
		COST PER ACRE-FOOT	**$ 35.61**
		Benefit to Cost	**7.16**

In preparing these estimates, and calculating the benefit to cost ratios, NAWC applied a multiplier of 0.9 to the project yield of the aerial component. It was determined that there would be an average of ten storms that would merit a flight per season. Of those ten storms it is very likely that problems originating from flight path approvals or aviation mechanics would prevent one flight per season. NAWC felt it necessary to account for this circumstance in NAWC's calculations of the benefit to cost ratios and the estimated average total costs per acre-foot.

As indicated in the tables, the added complexity of aircraft seeding does reduce the benefit to cost ratio. This does not, however, mean the aircraft should inherently be excluded, but there should be careful consideration about the benefit of the additional 3,442 Acre-feet that are projected to result from aerial seeding. Members of the SAWPA Commission will need to determine what they feel the optimal level of investment in a cloud seeding program should be. They may want to wait until after contractors have submitted their proposals with completed operational designs before making this decision.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The American Society of Civil Engineers (ASCE) report entitled "Guidelines for Cloud Seeding to Augment Precipitation, Third Edition" states that when conducting seeding feasibility studies, a proposed program must demonstrate feasibility both technically and economically for the program to be considered feasible. NAWC has followed ASCE Guidelines and Standards in the preparation of this Report (ASCE, 2016 and ASCE, 2017). Consequently, comments may be made regarding the technical and economic feasibility of the proposed SAWPA program. The conclusions on feasibility of the proposed program are as follows.

6.1.1 Technical Feasibility of Cloud Seeding for the Four Potential Target Areas

Four potential target areas were selected within the SAWPA River Basin: Northwest (NW), Northeast (NE), Southeast (SE) and Southwest (SW). These selections were largely focused on higher elevation areas which contribute the bulk of the runoff into the Santa Ana River Basin.

Fifty-eight storms over a five-year period were carefully analyzed to determine their seedability. Roughly 64% of the storms were deemed seedable by ground-based seeding systems, with an additional 17% of storms deemed seedable exclusively by aircraft. Estimated increases for each target area are included in Table 4.1.

CNGs were selected as the primary ground-based seeding system for the NW, NE and SE target areas as they are more economically favorable and provide continuous plume coverage. For the SW target area, AHOGS systems were recommended exclusively. Due to the narrow land barrier that forms the SW target area, only convective bands would provide enough lift and mixing to produce desirable results within the storm system before they pass over the target area. The higher concentration release from burn-in-place flares are more favorable for the convective systems. HYSPLIT dispersion modeling indicates that the dispersion from the 14 proposed ground sites would typically provide good coverage over the target areas under varying storm conditions.

As 17% of the storms were found to be seedable exclusively by aircraft the technical feasibility of an aircraft program was considered for each of the four target areas. An aerial component was only deemed technically favorable for the NE Target area. This area meets geographical and climatological requirements to support an aerial component. This is also the furthest target area from major international airports improving the likelihood of FAA approval and cooperation. It can be difficult to get FAA approval for a seeding flight during times of high traffic; unlike typical flights that quickly leave crowded airspace, seeding flights run the same track for an extended period of time. The ideal flight path for the SW target area would be in direct conflict with airspace used by both Los Angeles International (LAX) and John Wayne Airport (SNA) for holding patterns and is therefore not feasible. Similarly, the proximity of the NW target area to the Ontario and other International Airports would render an aerial program challenging. Due to the geography of the SE target area, NAWC does not believe an aerial component would prove economically favorable for this area.

From the RFP for Task 4 "The Consultant shall determine if a cloud seeding program is feasible at the recommended target locations within the Santa Ana River Watershed". The RFP indicates this determination will be based upon both the technical and economic feasibility of the proposed program as suggested in the ASCE 2016 publication.

Though potential limitations for flight path approvals during storm events exist, NAWC concluded that the program, as proposed and specified in this design study, is technically feasible.

6.1.2 Economic Feasibility of Cloud Seeding for the Four Potential Target Areas

The hydrological data analysis section (Section 4.4) estimated the average annual runoff amounts from the NW, NE, SW and SE target areas as 25,000 AF, 65,000 AF, 5,000 AF and 10,000 AF, respectively rendering an estimated total for the four areas of 105,000 AF. A general approximation of the economic feasibility of seeding the four potential target areas can be made at this point, (with data referenced from Table 4.1 in section 4 of this report).

Table 4.1

Estimated Precipitation and Streamflow Increases

Target Area	Seasonal Precipitation Increase (inches)	Percent Increase	Avg. Natural Streamflow (AF)	Streamflow Increase (AF)	Percent Increase
NW	0.41	3.5%	25,000	2,043	8.2%
NE (ground)	0.49	4.1%	65,000	4,330	6.7%
NE (air)	0.89	7.3%	65,000	3,442	5.3%
SW	0.59	3.7%	5,000	447	9.0%
SE	0.49	4.5%	10,000	1,373	13.7%
	TOTAL w/ Ground Only		**105,000**	**8,193**	**7.8%**
	TOTAL w/ Ground and Air		**105,000**	**11,635**	**11.1%**

The combined total estimated streamflow increase (due to seeding) from the four areas is 8,193 AF with only ground seeding in the NE area and 11,635 AF with both ground and aircraft seeding in the NE area. From an analysis provided in Appendix C there are indications of larger increases in streamflow in wet years versus those from average or dry years rendering these estimates conservative.

With a typical wholesale value around $255/AF, the additional runoff from cloud seeding would be valued between $2,000,000 and $3,000,000 (if fully allocated). After careful review of the predicted costs associated with running the cloud seeding program, and after considering the potential yield, NAWC has determined the following:

1. An exclusively ground-based program, as described in this feasibility study, would exceed the ASCE's recommended 5:1 benefit cost ratio with an estimated 10:1 benefit to cost ratio.
2. A dual program, with both aerial and ground support, would increase production but at a lower efficiency, yielding roughly a 7:1 benefit to cost.

It is concluded that the proposed program would be economically feasible and that the ASCE requirements that a proposed program would be both technically and economically feasible for the Santa Ana River Watershed would be met.

A ranking of the technical and economic feasibility of each of the four target areas based upon the estimated average increases in annual streamflow would be: NE, NW, SE, and SW. This ranking is based off the total annual runoff in a given season (to which estimated seeding increases may be applied) and the hydrology of these areas.

6.2 Recommendations

6.2.1 RFP Considerations

It is NAWC's recommendation that a program designed to impact rain and/or snow fall in all four target areas cost no more than $450,000 per year. This is based on an estimated value of $255 per acre-foot, for untreated and unpressurized imported water and the likely resulting favorable benefit/cost ratios.

If during, the RFP process, a contractor suggests only operating in 1 or 2 of the 4 target areas, the maximum yield of the program will be diminished, reducing the total program value. Reductions should be made accordingly to accepted bid limits. Limiting the scope of the program could have a significant impact on the benefit to cost ratio and overall program efficiency.

Should an RFP be released for the purpose of selecting a cloud-seeding contractor, it is NAWC's recommendation that the following considerations be addressed in the RFP:

Recommended minimum requirements for contractors participating in the RFP include:

- Evaluation Methodology - NAWC would encourage SAWPA to require all RFP participants to carefully describe their evaluation strategy, in detail, and include the data sets and mathematical models that will form the foundation of their evaluations. It is best to request this information upfront in order to ensure that it is prepared without bias (i.e. an *a priori* instead of *a posteriori* analysis technique).
- Weather Modification Association Certified Manager – At least one managing member of the Contractors team should be a Certified Manager by the WMA. An alternative certification would be an AMS (American Meteorological Society) Certified Consulting Meteorologist (CCM) with a cloud-seeding specialty.
- Weather Modification Association Certified Operator – Any meteorologist making seeding decisions must be a Certified Operator by the WMA.
- Bachelor of Science degree in Meteorology – The individual operating the program must hold a Bachelor of Science degree in Meteorology. Having one team member or managing member with a Master of Science in Meteorology is recommended.
- Experience with operating a precipitation enhancement program in the State of California. Due to the unique climatology of California and the unique legal and environmental considerations, preference should be given to contractors with recent and extensive experience operating in California.

- Experience operating cloud seeding program in or around areas where wildfires are common. Experience operating programs in areas directly impacted by large wildfires, with experience navigating runoff and debris flow concerns.
- Liability insurance – A general liability policy with a consequential effects rider with the agency issuing the contract listed as “additionally insured.” Quoting from the ASCE Standard Practice for the Design and Operation of Precipitation Enhancement Projects (ASCE 2017, section 3.6.1): “Sponsors shall request weather modification service contractors to provide liability insurance against the effects of operations. This special insurance is termed “consequential loss insurance” and is normally not part of ordinary liability insurance”.
- The SAWPA commission may be able to obtain copies of previous RFP’s recently prepared by other agencies in California to conduct operational cloud seeding programs. Such RFP’s may assist SAWPA in the preparation of their RFP. For example, various requirements of other agencies might assist SAWPA in preparing a comprehensive list of items/requirements to include in their RFP.

6.2.2 CEQA

If the SAWPA commission elects to move forward with an RFP and a weather modification program, the California Environmental Quality Act (CEQA) will require the development of a Mitigated Negative Declaration (MND). The development of an MND is often a lengthy and involved process (generally 6-12 months). If the SAWPA Commission desires to implement a Cloud Seeding program, NAWC recommends they begin working on their MND as soon as determined feasible. NAWC has aided the Los Angeles County Department of Public Works, Santa Barbara County Water Agency, San Luis Obispo County and Sacramento Municipal Utility District in the development of their cloud seeding MND’s and can be contracted to assist in this work on behalf of SAWPA.

6.2.3 Microwave Radiometer

A useful tool in assisting with feasibility studies and operational winter cloud seeding programs is an instrument called a microwave radiometer. A radiometer placed in an area before the inception of an operational cloud seeding program would provide data critical to the development and improvement in a program design of a weather modification program. Figure 6.1 shows a photo of a microwave radiometer used in a past NAWC feasibility study.

Figure 6.1 **Microwave radiometer**

A microwave radiometer measures atmospheric bright body temperature. This bright body temperature is then used in algorithms within the radiometer to derive several different parameters including temperature, relative humidity, any atmospheric stability layers and, most importantly to the field of weather modification, liquid water. With the two variables of temperature and liquid water, one can determine if the liquid water is in fact, supercooled. This is important as SLW (water that exists as a liquid at temperatures colder than -5°C) is the target of glaciogenic cloud seeding. Most weather systems contain some SLW, ranging anywhere from minimal to large amounts. It is this supercooled liquid water interacting with ice nuclei, either naturally or in cloud seeding operations (silver iodide) that can create snowflakes and in cases where melting occurs, rain. Systems in the Intermountain West generally contain somewhat less supercooled water, as colder systems contain less liquid water than the warmer, more robust systems that often affect California. Convective bands that frequently occur in coastal California winter storms, are generally recognized to contain large amounts of supercooled liquid water.

Temperature data observed by the radiometer can be converted into upper level sounding information in real-time, like that provided by National Weather Service weather balloon observations (known as rawinsondes). These soundings can be useful in identifying several different parameters important to cloud seeding operations and post-storm analysis. If a radiometer is utilized on an operational winter program or prior to the formation of an operational program, the temperature information along with the SLW information can be provided to the project meteorologist on a continuous, real-time basis. This means that the project meteorologist can derive an upper air temperature sounding at any time, versus the National Weather rawinsonde observations which are only taken twice per day at relatively scattered locations across the United States. Such information is especially useful in the conduct of ground-based cloud seeding operations.

Figure 6.2 shows an example of a processed radiometer time cross-section plot from the Simi Valley location, where the top panel shows temperatures in degrees Celsius, the middle panel shows relative humidity with respect to water and the bottom plot shows liquid water in g/m^3. Liquid water values of 0.10 g/m^3 or less are usually deemed minimal amounts which are likely not conducive to effective seeding. Liquid water amounts of 0.10-0.50 g/m^3 or greater are more indicative of colder winter systems that have some glaciogenic seeding potential. Convective type weather systems have been shown to have values much higher than this, ranging as high as 3.00 g/m^3 (Linacre & Geerts, 1999) In short, the greater the amount of liquid water that is supercooled, the better a potential target for glaciogenic cloud seeding.

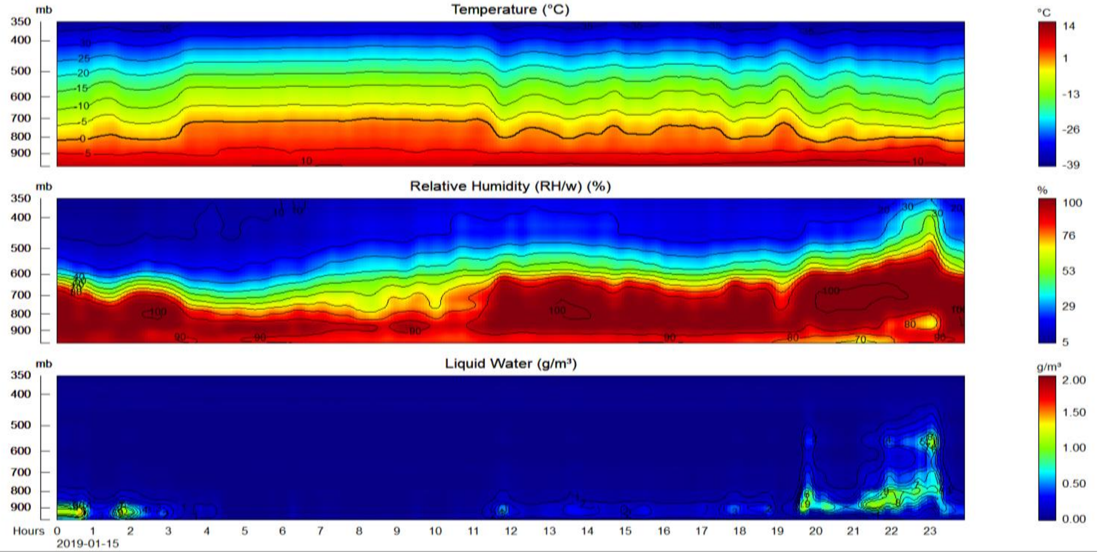


Figure 6.2 **Radiometer plot from Simi Valley, California on January 15, 2020.**

The three parameters discussed were observed during a convective band passage over the radiometer on January 14-15, 2020. At around 0000 UTC, or 1600 PST on the 14th, liquid water was observed near the surface. Temperatures during this time period, as observed by the radiometer, were near or above freezing. This was likely some prefrontal precipitation ahead of the main convective band that moved through around 2000 UTC, or 1200 PST on the 15th. The temperature plot in the upper panel of Figure 6.2 shows that the atmosphere cooled somewhat; however, more notably in the lower panel, liquid water extends higher in the atmosphere during the latter part of the time period. The liquid water plot shows measurable amounts starting around 900 mb or 3,200 feet MSL and extending up to around 600 mb where the temperature is as cold as -15°C. This result is encouraging in terms of the indication of seeding potential in this case since the SLW must be colder than approximately -5°C for the silver iodide nuclei to become active. The plot shows a high amounts of supercooled liquid water during this convective band passage, with liquid water values between 0.50-1.3 g/m^3 observed. This range has been frequently observed in convective bands along frontal zones in California.

The radiometer can be placed wherever the user desires to observe the atmospheric conditions related to storm seedabilty. NAWC has deployed several radiometers in the field during operational cloud seeding projects. For example, one in support of a feasibility study conducted in Utah (Beall et al., 2018). Radiometers deployed in support of operational programs help with real-time targeting decisions and learning more in post analysis about a particular area’s seedability (Beall et al., 2017).

A microwave radiometer could be operated in conjunction with the first winter season of operations from a central location that would be representative of the four target areas. This would help verify NAWC’s assumptions about the location, frequency, and magnitude of SLW occurrences within these areas. Such an application would provide observations to validate various computer models that are available that predict liquid water and temperature fields and document the presence of low-level inversions during seedable periods.

The placement and operation of the radiometer would assist in validating operational considerations, including:

- The ideal concentration of Silver Iodide solution, as well as the Ideal burn rate of Silver Iodide flares.
- How operations should be handled during storm events that were preceded by atmospheric stability.
- Critical elevations, including the typical elevation of stable layers and the typical elevation of liquid water maxima within storm systems.

Neither a Mitigated Negative Declaration (MND) nor any type of seeding permit would be required since the radiometer is a passive non-environmentally invasive system.

6.2.4 Final Considerations

NAWC has determined that a cloud-seeding program in the Santa Ana Watershed would far exceed the minimum recommended ASCE benefit/cost threshold. If such a program is pursued, NAWC recommends beginning with a ground only program. NAWC believes such a program would maximize the return on investment and would have a substantial impact on annual runoff. NAWC recommends that a detailed evaluation occur after the first 3 years of operation and annually from that point forward. The first evaluation would benefit from the implementation of a radiometer study (if a radiometer study is not performed prior to the first year of operation). The combination of a three-year performance evaluation, and placement of a radiometer would provide ample evidence to determine if aerial seeding should also be implemented at that time.

NAWC also encourage the SAWPA commission to continue working with the North American Weather Modification Council (NAWMC). The NAWMC is an incredible resource for public entities who are currently operating or looking to implement a weather modification program.

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APPENDIX A: STORM PERIOD ANALYSIS

Examples of Meteorological Analyses and Streamflow Regressions

Note: This is a subset of the types of data analyses conducted as part of this study for the North East Target

Table A.1 Meteorological Analysis for the NE Target Area

Date	**Time Range (UTC)**	**Notes/Description**	**-5°C Height**	**700 mb**			**850 mb**			**Stability**
			(m)	**Temp (°C)**	**Wind (kt)**	**Wind dir**	**Temp (°C)**	**Wind (kt)**	**Wind dir**	
November 20, 2010	16-23	Disorganized, showery	3100	-4	35	WSW	5	20	WSW	Mostly stable below -5 C level
December 6, 2010	00-12	Disorganized, convective	3900	0	30	SW	11	20	SSW - WSW	Multiple stable layers
December 16, 2010	12-18	Weak bands		-1	40	W	5	15	WNW	Quite stable 900-700 mb
December 19-20, 2010	21-10	Disorganized bands	3700	-2	40	WSW	8	25	WSW	Mostly well mixed
December 20-21, 2010	20-20	Stalled band for ~ 24 hours		-3	45	WSW	6	35	SW	One or two stable layers
December 22-23, 2010	00 (22) - 03 (23)	Multiple bands, areas of mod-heavy rain	3250	-3	40	SW	7	35	SW	Mostly well mixed
December 26, 2010	04-08	Strong, fast-moving band, some conv		1	40	WSW	5	20	WSW	Very stable 850 mb to -5 level
December 29, 2010	12-21	Broad precip band, mostly stratiform		-5	45	WSW	2	35	WSW	Some stability 900 - 700 mb
January 2-3, 2011		Radar data missing?								
February 16, 2011	08-23	Scattered convective activity		-1	45	WSW	7	35	WSW	Some stability 900 - 750 mb

February 19, 2011	00-12	Disorganized bands, mostly convective		-5	50	SW	4	40 to 25	S - WSW	Mostly well mixed
February 20, 2011	00-12	Scattered, showery activity		-11	25	SW	-1	20	SW - W	Well mixed
February 26, 2011	03-16	Broad, slow-moving band		-6	40	WSW	2	35	SW	Slightly stable above 800 mb
February 26-27, 2011	18 - 04	Post-frontal shower activity, orographic		-13	25	SW	-4	20	WSW	Well mixed
March 20-21, 2011	16-09	Broad band, strat + convective		-9	35	SW	2	25	SW	Well mixed
March 21, 2011	10-22	Convective showers in trough core		-10	30	WSW	0	20	WSW	Well mixed
March 25, 2011	12-15	Weak band of showers		-5	35	W	2	20	W	Quite stable above 800 mb
December 2-3, 2014	22-10	Broad band then showers, mostly strat		2	30	WSW	11	30	WSW	Stable layers sfc-850, MALR above
December 3-4, 2014	12-16; 23-15	SHRA band, then MDT SHRA; conv		2	15	W	9	10	SW	Well mixed
December 12, 2014	12-15; 16-00	LEWP band, then wide band, then SHRA		0	30	SW	8	30	SW	Stable 925mb, stable lyrs above 800
December 13, 2014	00-08	Showers, some moderate/hvy		-4	35	SW	6	35	WSW	Well mixed
December 31, 2014	01-15	Area of light rain		0 to -11	50 to 10	W	0	10	WSW	Well mixed below 750; strg inv 750
January 11, 2015	08-00	Showers moving onshore all day		-2	15	S	7	10	SW	Well mixed
January 26-27, 2015	21-07	Bands of SHRA mvg in from S to N		1	10	SW	9	10	S	Mostly well mixed
February 22-23, 2015	22-13	scattered convective showers		-3	35	WSW	4	20	WSW	Well mixed
March 1-2, 2015	01-01	sct SHRA then waves of rain		-8	30	WSW	3	10	SW	Well mixed
March 2, 2015	09-15; 18-22	MDT SHRA band; cluster SHRA		-8	20	W	2	15	SW	Well mixed

December 14, 2015	03-10	SHRA mvg NW to SE with mtn SHRA		2 to -9	40	NW	7 to 1	20	NW	Well mixed, esp. later on
December 20, 2015	01-06	Disorganized SHRA band W to E		-3	25	W	4	5	SW	Mixed, but stable layer 800-850
January 5-6, 2016	16-08	Area of MOD/HVY rain, upslope late		-4	30	W	6	25	SW	Well mixed
January 6-7, 2016	18-16	Waves of RA/SHRA, some HVY		-6	40	W	3	30	W	Well mixed
Jan 31 - Feb 1, 2016	16-06	Orographic north mtns		-4	65	WSW	6	50	W	Well mixed
February 17-18, 2016	23-13	Broad band RA/RA+ w/ trailing SHRA		3	45	WSW	10	25	SW	Some low level stability
March 6, 2016	10-18	Disorganized band of RA/SHRA		0	40	W	8	20	W	Strong stability at 850, mixed below
March 7, 2016	14-17; 19-22	Main SHRA+ band; 2nd SHRA band S		-5 to -11	30	WNW	1	15	WNW	Well mixed, some stability 800 early
March 11-12, 2016	22-02	MDT SHRA band mvg W to E		-2	35	SW	6	25	SW	Mixed, but MALR 925-600
April 7-8, 2016	17-07	RA/SHRA mvg NW across area		1	20	S	10	10	S	Becmg well mixed, deep moist layer
April 9-10, 2016	19-03	Sct SHRA mvg N		-1	20	S	7	15	SW	Well mixed, stable layer near 700
November 21, 2016	06-12	Statiform band, mixed strat/ conv shwrs		-4	40	SW	5	25	SW	Well mixed
November 27, 2016	18-23	Scattered/ orographic		-5	20	WNW	3	20	WNW	Stable above -5 C level
December 16, 2016	02-20	Disorganized stratiform / weak conv		0	50	WSW	9	30	WSW	Strong stability below 900 mb
December 22, 2016	02-22	Disorganized subtropical, mostly strat		-1	25	SSE	9	25	S	A little stability near surface
December 24, 2016	04-14	Broad band, mix strat/conv		-7	30	SW	0	25	WNW	Mostly well mixed

December 31 - January 1	23-06	Trough core with some banding		-3	35	SW	4	15	SW	Stable near 750 mb
January 9, 2017	07-17	Main band passage after 12Z								
January 12-13, 2017	12-12	Disorganized/orographic/convective		-5	30	SW	3	25	SW	Well mixed
January 19, 2017	11-17	Disorganized/strat/ conv		-4	30	WSW	3	30	SW	Stable layer 800-850 mb
January 20, 2017	00-00 (21)	Disorganized/ orographic/ convective		-4	65	SW	4	45	W	Well mixed
January 22-23, 2017	09-02	Disorganized mostly stratiform		0	60	WSW	6	45	SW	Quite stable 780 to 900 mb
February 6, 2017	14-18	Disorganized, showery		0	40	WNW	6	20	W	Very stable above 850 mb
February 11, 2017	01-09	Rapidly weakening band, stratiform		0	45	WSW	6	25	WSW	Slightly stable
February 17-18, 2017	23-10	Broad, N-S oriented band mostly stratospheric		-5	var	SSW to W	3	var	SW	Well mixed
February 27-28, 2017	19-06	Disorganized, showery		-4	30	WSW	4	20	SW	Well mixed
January 9, 2018	01-22	Disorganized, Stratospheric/ Convective		3	45	SSW	10	50	S	Isothermal layer 830 - 900 mb
January 9-10, 2018	22-03	Compact band around low center		-6	35	SW	3	30	SW	well mixed
February 27, 2018	07-12	Distinct band passage		-8	30	SW	-1	25	WSW	Stable layer (frontal) 800-900 mb
March 11, 2018	01-09	Disorganized, mostly stratiform		1	25	WSW	8	25	SW	Somewhat stable below 700 mb
March 15, 2018	06-13	Mostly convective/ orographic		-5	30	WSW	4	30	WSW	well mixed
March 22-23, 2018	17-10	Disorganized/ convective		0	30	WSW	6	25	WSW	stable layers (?)

Table A.2 Big Bear Lake vs. Santa Ana River Streamflow Regression.

*Due to the size of the excel sheet being represented here, it is recognized that formatting anomalies exist.

	Big Bear Lake	Santa Ana River near Mentone												
Year	Nov-Apr precip (inch)	Nov - Oct streamflow (acre-ft)												
1961	7.94	16295.75146												
1962	24.52	33557.84998												
1963	12.1	17711.45388												
1964	16.95	17649.07372												
1965	17.01	20244.39594												
1966	27.23	53696.03104												
1967	36.03	89066.87269												
1968	15.9	33211.83347												
1969	51.88	212631.4135												
1970	11.9	36261.66806												
1971	14.55	30651.66827												
1972	14.52	29378.32948												
1973	26.43	55158.04752												
1974	16.29	38323.93245												
1975	11.9	32162.32937												
1976	13.13	30893.85008												
1977	6.29	22516.26362												
1978	34.2	104169.3184												
1979	25.99	106500.7398												
1980	36.29	216066.6365												
1981	7.55	37815.3209												
1982	19.22	53933.65087												
1983	28.66	160578.0436												
1984	8.91	47074.31228												
1985	8.9	30882.8914												
1986	18.89	43874.081												

1987	11.75	24849.37097												
1988	10.39	21734.37935												
1989	11.53	19225.48688												
1990	11.08	13187.64248												
1991	14.8	25201.13955												
1992	16.55	37220.37877												
1993	40.48	168558.44												
1994	15.76	37431.32091												
1995	29.38	123462.2929												
1996	14.36	44101.48595												
1997	10.62	39884.37867												
1998	15.01	114009.566												
1999	4.6	27872.52788												
2000	12.22	21375.76779												
2001	9.76	16077.56965												
2002	4.46	9770.528559												
2003	18.9	24267.07347												
2004	10.44	16708.44235												
2005	32.62	119283.1195												
2006	13.99	54157.73351												
2007	3.45	18921.27202												
2008	18.53	31757.20542												
2009	13.54	22216.0157												
2010	29.56	45614.18011												
2011	27.87	87338.34714												
2012	7.89	26824.31304												
2013	7.27	17606.45884												
2014	10.09	13089.68877												
2015	12.16	13706.58792												
2016	15.03	13293.63917												
2017	23.19	34576.46151												
2018	8.41	14925.67878												
2019	32.32	56159.00616												

Avg	17.4777966	49571.41117		49571										
Precip + 4.1%	18.1908907		Resulting Streamflow	52323	1.05552	4.08% precip incr = 5.55% streamflow incr					2752	AF additional due to ground-based seeding		
Precip + 7.3%	18.7571713		Resulting Streamflow	54509	1.09961	7.32% precip incr = 10.0% streamflow incr					4938	AF additional due to aircraft seeding		
SUMMARY OUTPUT														
Regression Statistics														
Multiple R	0.8172478													
R Square	0.6678940													
Adjusted R Square	0.6620676													
Standard Error	27665.642													
Obs	59													
ANOVA														
	df	*SS*	*MS*	*F*	*Significance F*									
Regression	1	87737907451	8.77E+10	114.632	2.9E-15									
Residual	57	43627102944	7.65E+08											
Total	58	1.31365E+11												
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*						
Intercept	-17890.70956	7257.743613	-2.46505	0.016735	-32424.1	-3357.33	-32424.1	-3357.33						
X Variable 1	3859.875603	360.5125864	10.70663	2.9E-15	3137.962	4581.79	3137.962	4581.79						

APPENDIX B: STREAMFLOW AND PRECIPITATION DATA

Location of Stream and Precipitation Gauge Sites used in the Regression Modeling

Table B.1

Stream Gauge Sites

Name/USGS number	Latitude	Longitude
Northwest Target		
Lytle Creek 11062000	34.212	-117.457
Cajon Creek 11063510	34.263	-117.466
Northeast Target		
Devil Canyon 11063680	34.208	-117.331
East Twin Creek 11058500	34.179	-117.265
City Creek 11055800	34.144	-117.188
Plunge Creek 11055500	34.118	-117.141
Santa Ana River 11051499	34.108	-117.100
Southeast Target		
San Jacinto River 11069500	33.738	-116.833
Southwest Target		
Santiago Creek 11075800	33.709	-117.635

Table B.2

Precipitation Gauge Sites

Site Name	Latitude	Longitude
Northwest Target		
Mt. Baldy FC	34.23	-117.67
Lytle Creek PH	34.20	-117.45
Lytle Creek RS	34.23	-117.48
Northeast Target		
San Bernardino FS 226	34.13	-117.27
Lake Arrowhead	34.25	-117.18

Site Name	**Latitude**	**Longitude**
Santa Ana River PH 1	34.13	-117.07
Big Bear Lake Dam	34.23	-116.97
Big Bear Lake	34.25	-116.88
Mill Creek 2	34.08	-117.03
Southeast Target		
Mt. San Jacinto WS	33.80	-116.63
Idyllwild Fire Dept	33.75	-116.72
Hemet	33.75	-116.95
Southwest Target		
Elsinore	33.67	-117.33
Corona	33.87	-117.57
Tustin Irvine Ranch	33.73	-117.78
Santa Ana Fire Station	33.75	-117.87

APPENDIX C: ADDITIONAL COMMENTARY ON ESTIMATED INCREASES

Seasonal Variability in Seeding Effects Suggested by Precipitation and Streamflow Regressions

General Note:

For all these comparisons, the cloud seeding increase (percentage wise) is assumed to be the same for wet and dry years. This is probably a fair assumption, as the overall mix of storm types and their seedability is likely to be similar over the long term for drier and wetter seasons. Any inequalities regarding the underlying seedability of storms between wet/dry seasons would be difficult to deduce without a very large data set. Of course, based on this assumption, the magnitude (absolute value) of the precipitation increase due to seeding is proportionally greater for wetter seasons. The relationship between precipitation and streamflow, however, can vary dramatically and somewhat unexpectedly in certain areas when comparing wet and dry seasons, and that is the driving factor for this analysis.

Northwest Target Area

Regressions between the Lytle Creek Ranger Station (precipitation site ending in 2001) and the Lytle Creek stream gauge suggests that there is very little carryover from one year to the next, and the November – April precipitation is best correlated with the immediate water year runoff. Based on this result, this is likely an unregulated gauge site. The estimated seeding increase in streamflow obtained from this regression averaged for all years, and with the results of the smaller Cajon Creek included, were 2,043 AF for the NW target area.

An analysis of wet vs. average vs. dry years (19 dry, 19 "average" and 19 wet) shows that, similar to many other areas in this region, the wet years have about an order of magnitude higher natural runoff than the dry and average years. The average ranges from under 3,000 AF in dry years to between 3,000 to 4,000 AF in average years and then spikes to around 40,000 AF for the wet years (which is highly influenced by a few very wet years).

Streamflow increases due to seeding, which are based on an estimated 3.5% Nov-Apr precipitation increase in all seasons, average between about 400-500 AF both the dry and average set of years for Lytle Creek, increasing dramatically to an average of over 4,000 AF for the wet years. It should also be noted that for the dry and average sets, correlation was poor with R values of 0.37 and 0.59, respectively. For the 19 wet years, however, the correlation was very high with an R value of 0.93. Regressions of precipitation with Lytle Creek RS and Cajon Creek (at least a portion of which originates in the NW Target area) had only 21 years of overlap, which was not a large enough data set to analyzed in this way. However, if the smaller amount of runoff from Cajon Creek is added to that from Lytle Creek, the total estimated increases due to seeding were between 500-600 AF for the dry and average sets of years, and over 5,000 AF for the wet years. The results for this area suggest that somewhat over 80% of additional runoff here would also be produced during the wettest one-third of the years.

Northeast Target Area

Regressions for this area use November – April precipitation increases of 4.1% (ground seeding only) and 7.3% (with aircraft).

Regression with San Bernardino FS precipitation and Devil Canyon streamflow suggests no carryover of runoff. For 80 years in this regression, the driest and middle third all have about 700-800 AF of natural flow, with the correlation to precipitation appearing slightly negative (inverted) between these two sets. The wet third of years have 3700 AF average of natural flow. For the dry and average years, minimal (less than 100 AF for both ground and aircraft) increases are suggested, with 395 AF (ground only) and 710 AF (with aircraft) average seeding increase suggested for the wet years. Correlation is very poor for the dry and average years, and only fair (R = 0.70) for the wet years.

Note that for all years combined, the equation suggested a mean annual increase of 156 AF (ground only) and 280 AF (with aircraft). The runoff in Devil Canyon was better correlated with the Lytle Creek precipitation gauge (although with a shorter record of 57 years) which suggested mean annual seeding increases of 170 AF (ground only) and 306 AF (with aircraft).

Regression with San Bernardino FS precipitation and East Twin Creek streamflow suggests fairly minimal (< 10%) carryover of runoff to the next year, with a suggested carryover volume of 432 AF from regression involving dry years. This is reasonable as even the very driest years have runoff of over 600 AF. The correlation is not substantially better with the previous year precipitation included, however.

For 80 years in this regression equation, the 27 dry years have a poor correlation (R = 0.34) and a positive offset for runoff, which may possibly be due to a certain amount of carryover or base runoff from previous seasons. In any case, the natural flow averaged 1590 AF for these dry years with low increases suggested due to seeding (47 and 85 AF for ground and aircraft, respectively). The 26 average years have a moderate correlation (R = 0.60) and an average natural flow of 2262 AF. The implied increases are significantly more, 353 and 633 AF for ground and aircraft, respectively. For the 27 wet years, a good correlation (R = 0.82) is observed with an average runoff of just under 7,000 AF. The suggested increases due to seeding in the wet years are 598 AF (ground only) and 1072 AF (with aircraft).

For the combination of all years, the average estimated increases due to seeding for East Twin Creek are 267 AF (ground only) and 480 AF (with aircraft).

Regression with San Bernardino FS precipitation and City Creek streamflow suggests no carryover, with the equation showing a (slightly) negative coefficient to the previous year precipitation. For the 81 years in this regression equation, the 27 dry years have an average annual natural flow of 2471 AF, with a suggested seeding increase of 114 AF (ground only) and 204 AF (with aircraft). The correlation is fair with an R value of 0.53 for these dry years. The "average" years actually have a poorer correlation, R = 0.32. These years have an average natural flow of 3264 AF and implied increases of 262 AF (ground only) and 469 AF (with aircraft). The 27 wet years in the regression have a good correlation (R = 0.75) an average natural flow of 15,102 AF. The implied increases for these wet years are 1496 AF (ground only) and 2684 AF (with aircraft).

For the combination of all years, the average estimated increases in City Creek due to seeding are 639 AF (ground only) and 1147 AF (with aircraft).

Regression with San Bernardino FS and Plunge Creek suggests minimal carryover (< 10%), with the equation improving slightly (R = 0.906 vs 0.896) when adding the previous year (Nov – Apr) precipitation. There was a total of 51 years in the regression, and an implied carryover of over 400 - 600 AF based on the equations using the 17 dry years and 17 average years. Over 500 AF of streamflow was observed even in the very driest years which is consistent with this. This is similar to the results for East Twin Creek in this regard.

For the 17 dry years the correlation was fair (R = 0.59) but was very low for the 17 average years (R = 0.09). Average annual streamflow was 2064 AF in the dry years and 3283 AF in the average years. For the dry years, the equations suggest increases of 68 AF (ground only) and 121 AF (with aircraft). For the average years, the numbers were slightly higher with 106 and 191 AF, respectively (although this equation has a very low R value). For the 17 wet years, the correlation was very high (R = 0.92) and average annual runoff was over 12,700 AF. This equation resulted in increases of 1229 AF (ground only) and 2205 AF (with aircraft).

For the combination of all years, the average estimated increases in Plunge Creek due to seeding area 502 AF (ground only) and 901 AF (with aircraft).

Regression of San Bernardino FS and the Santa Ana River gauge near Mentone implies carryover around 19% (following year) and around 26% (following 2 years). This is a very long regression, going back to 1913 and ending in 2004, although with a few missing years. Similarly, the better correlated (but somewhat shorter, 1961-2019) regression between precipitation at Big Bear Lake and the Santa Ana River gauge implies carryover over 15% to the following year and around 25% to the following 2 years combined. For both precipitation sites, the regression to the Santa Ana River improves somewhat when adding precipitation from previous November – April seasons. This result is not surprising, given that Big Bear Lake has a larger storage capacity (73,000 AF), larger than the average annual runoff in the Santa Clara River.

For dry years (depending on which precipitation gauge is used and the resulting period of record), natural flow at this gauge site is roughly 23,000 to 30,000 AF. Indications are that during these years, seeding would generate about 1,100-1,600 additional AF (ground-based only) and roughly 2,000 to 3,000 AF with aircraft. The sets of average years in these two regressions had roughly 34,000 to 38,000 AF of natural flow, with similar amounts of additional streamflow suggested as in the dry years (about 1,150-1,200 AF for ground-based only and 2,000 to 2,200 AF with aircraft). It should be noted, however, that both equations exhibited lower correlation for the set of average years than for dry years, so the results for years in the "average precipitation" category may be more uncertain.

For wet years, natural flow in the Santa Ana River averaged from 94,000 to 104,000 AF for the wettest third of seasons in regressions utilizing two gauge sites (San Bernardino FS and Big Bear Lake). Correlations were better in general for the wet years, although using Big Bear Lake precipitation resulted in a much better R value (R = 0.83 compared to 0.64). Indications of increases due to seeding were much higher for these years as well, ranging from 7,300 to 8,600 AF for ground-based seeding to between 13,000 to over 15,000 AF with aircraft included.

In sum, for the NE Target area, natural runoff ranges from about 33,000 AF in dry years to an average of over 136,000 AF in wet years. For ground-based seeding producing a 4.1% seasonal precipitation increase, indications are that additional streamflow produced would range from about 1,460 AF in dry years to just over 11,700 AF in wet years. If aircraft seeding in included with a seasonal precipitation increase of 7.3%, yield estimates range from about 2,570 AF in dry years to over 21,000 AF in wet years. For this target area, the equations imply that about 77% of streamflow increases due to seeding would be produced in the wettest third of years.

Southeast Target Area

The indicated average (for a 4.5% Nov-Apr precipitation increase) is 1,373 AF for a 71-year regression period. The distribution here is also highly skewed to higher precipitation years, with regression equation (based on two precipitation sites during Nov-Apr) suggesting around 200 AF or less of additional runoff likely produced in the drier third of years from cloud seeding. Depending on the period record used, the drier one-third of years had less than 2,000 AF of base flow (and perhaps as low about 1,000 AF).

For a year in the middle third, base flow of about 2,000 to 4,000 AF with increases from seeding of anywhere from about 250 to over 700 AF likely, depending on the equation used.

For the wettest third of years, average natural annual flow amounts of 25,000 to 30,000 AF were observed, with cloud seeding likely to generate about an additional 3,000 AF of runoff on average in these years. The implications are that over 80% of the additional runoff due to seeding would be produced in the wettest third of years for this area.

Another factor noted in the SE target area (using the San Jacinto River gauge near San Jacinto) is that significant lag time (or carryover of water from one season to the next) is indicated. If regression equations are developed using precipitation from current and past seasons, there are indications that perhaps 30% or more of the runoff from precipitation in a given season is instead measured at this gauge in the subsequent two years. This is likely the result of Lake Hemet (14,000 AF capacity) located about 10 miles upstream from the gauge site. One of the implications of this finding is that the regular regression equations (comparing a given Nov-Apr precipitation total at a measurement site to the streamflow during that year) are likely to underestimate the total that would be generated from a precipitation increase due to seeding. That is, a streamflow increase of 14% due to seeding in an individual season may be excluding a significant amount of increase which is contained in later runoff. If the precipitation is increased by 4.5% for three consecutive Nov-Apr seasons, an approximately 20% increase in runoff is implied by the equations. If this is true, it would mean that the true average annual increase in runoff may be closer to 2,000 AF from seeding in this area.

Southwest Target Area

Although indicated long-term average increase (for a 3.7% Nov-Apr precipitation increase) is around 450 or 500 AF of additional streamflow, the distribution is highly skewed toward high precipitation years. For the drier third of years (what one would typically call a "dry" year), only very sporadic runoff (based on streamflow in Santiago Creek) appears to occur. Equations suggest only a 20-50 AF increase in these years, with total natural runoff in these years averaging around 700 AF. Also, the precipitation vs. runoff relationship during these years has a low correlation ($R < 0.50$), suggesting only sporadic runoff during a few heavier precipitation events.

For an "average" year (middle third of the data set), increases of around 120-140 AF are suggested with a typical natural or base annual runoff of around 2,000 AF. Runoff during these years also appears quite sporadic and probably limited to heavier events, with a low to moderate correlation (R values about 0.35 to 0.75).

For a "wet" year (wettest third of the data set), much greater increases of around 1,000 to 1,300 AF are indicated with average natural runoff amounts of around 12,000 to 15,000 AF in these years. These wet years appear to generate sustained runoff, with a much higher correlation (R > 0.75) between the Nov-Apr seasonal precipitation total and the total annual runoff. These are the main years in the data set that are driving the overall "good" correlation between precipitation and streamflow for this area.

Obviously, the implication for this area is that wetter years seem to be a necessity in order to obtain a very effective cloud seeding increase to streamflow, with likely over 85% of the total increases to runoff generated during the wettest one-third of years. If the water can be stored effectively (and the storage is not used up in a typical season), then the resulting increases obtained during wetter seasons could be utilized during dry years. Of course, the possibility of a string of dry seasons and difficulty with seasonal forecasts may make such planning somewhat difficult.

Summary/Observational Comments

It should be noted that in general, for all of the target areas examined, the wet years provide a much better precipitation/streamflow correlation than either the dry or average years. Thus, the estimates of streamflow increases (due to seeding) in the wet years have a much higher confidence level than estimates for the other years in the regressions. In most cases, the dry and "average" years share a lot of similarity in terms of the regression equations, base flow numbers, and estimated increases, while the wet years are very different in regard to all of these results. The wet years seem to account for the vast majority of not only natural runoff but also increases due to seeding, with approximately 75-85% of these estimated increases attributed to the wet years. This percentage was highest for the SW target area (over 85%), and lowest for the NE target area (around 77%). In a few areas (likely the SE target area and the Santa Ana River downstream of Big Bear Lake in the NE target area), significant carryover from one year to the next, likely due to reservoir storage, impacts the results of the equations. For this reason, precipitation increases applied to multiple subsequent seasons are likely to generate the most accurate seeding increase estimates for these areas. For most of the target areas in general, the various regressions (particularly those utilizing the wetter years) suggest that the estimated seasonal precipitation increases (ranging from 3.5% to 4.5%) result in increases to annual total streamflow in the neighborhood of roughly 7-10%. However, the SE target area may be an exception to this, with total streamflow increases approaching 20% suggested when a seasonal precipitation increase of 4.5% is applied to consecutive seasons in that area (correcting for the apparent carryover issue). A streamflow increase approaching 14% was implied there even when applying the precipitation increase to only a single season.

APPENDIX D: SUPPLEMENTAL HYSPLIT MODEL RUNS

HYSPLIT Model Output for Additional Storm Events

These HYSPLIT model runs were conducted using the original 19 sites initially suggested in the first report submitted to SAWPA, prior to a revamping of the suggested site locations.

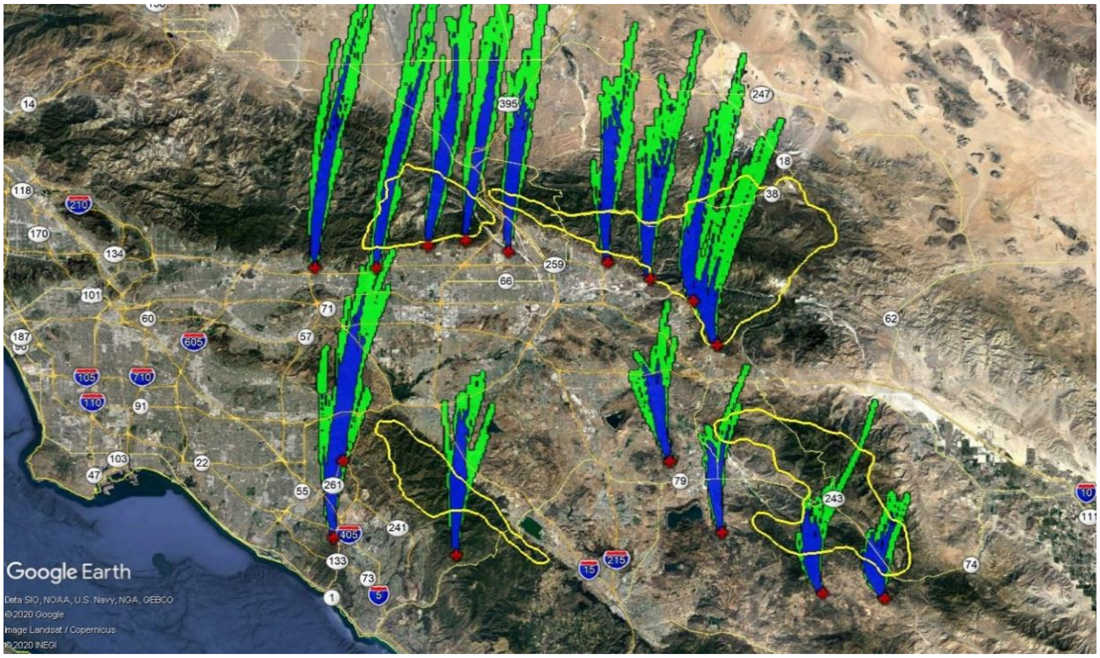

Figure D.1 One-hour projected plume dispersion from all ground sites valid at 2100 PST on February 18, 2011.

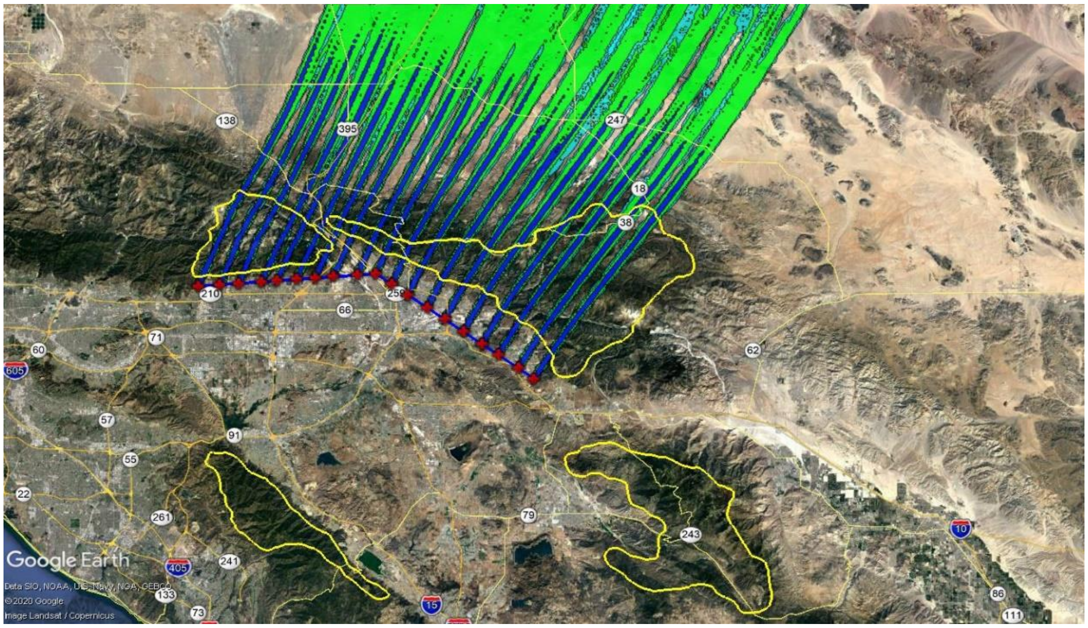

Figure D.2 One-hour projected plume dispersion from flight track at approximately 10,500 feet above sea level, valid at 2100 PST on February 18, 2011.

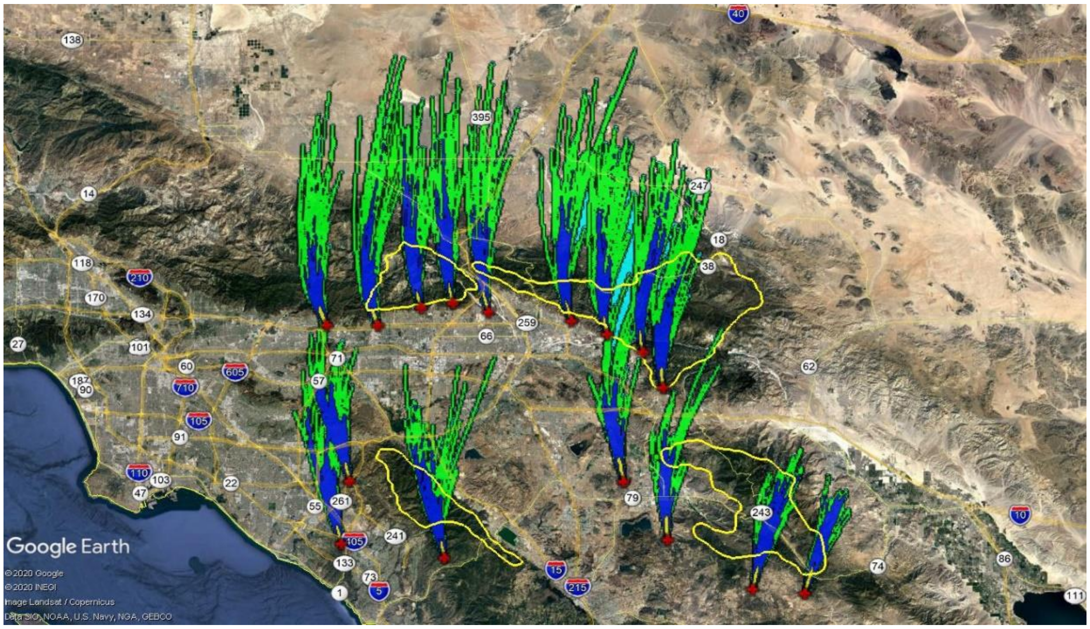

Figure D.3 One-hour projected plume dispersion from all ground sites valid at 2200 PDT on March 20, 2011.

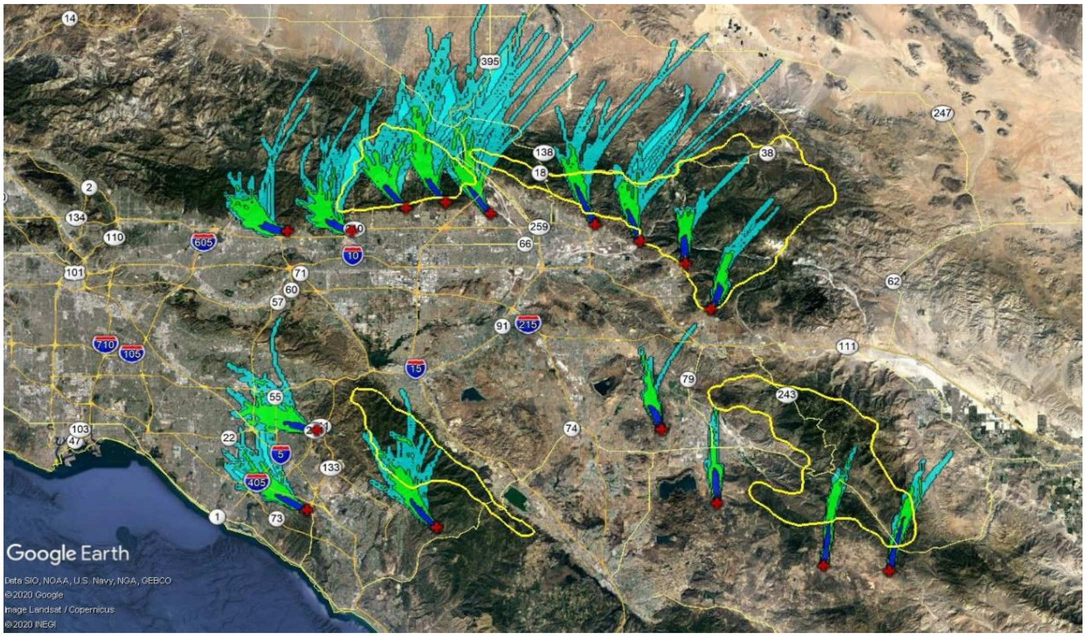

Figure D.4 One-hour projected plume dispersion from all ground sites valid at 1500 PST on December 2, 2014.

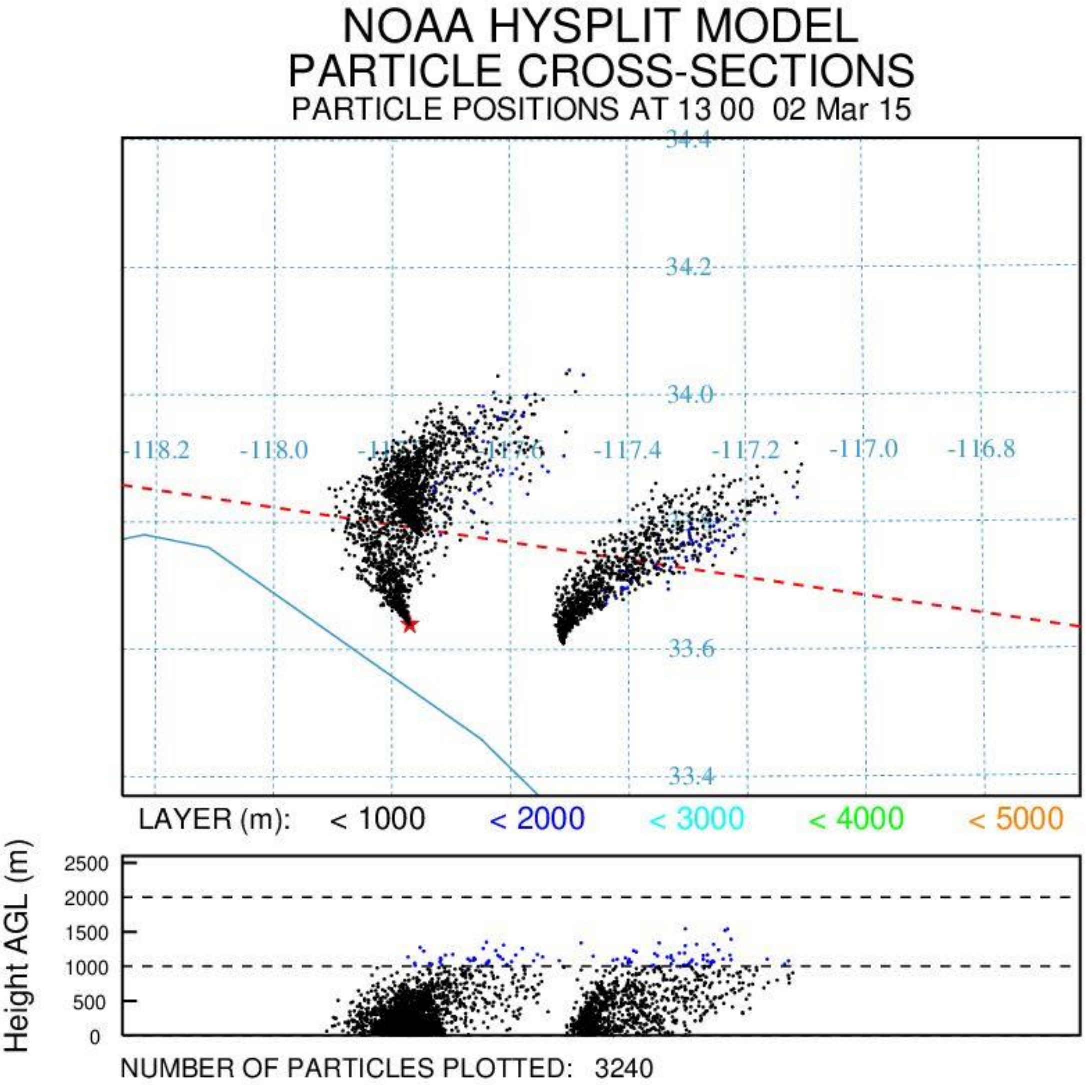

Figure D.5 Three-hour projected plume dispersion from southwestern sites with cross-section valid at 0500 PST on March 2, 2015. Note that top of plumes extended to about 1500 m (approx. 4900 ft) above ground level.

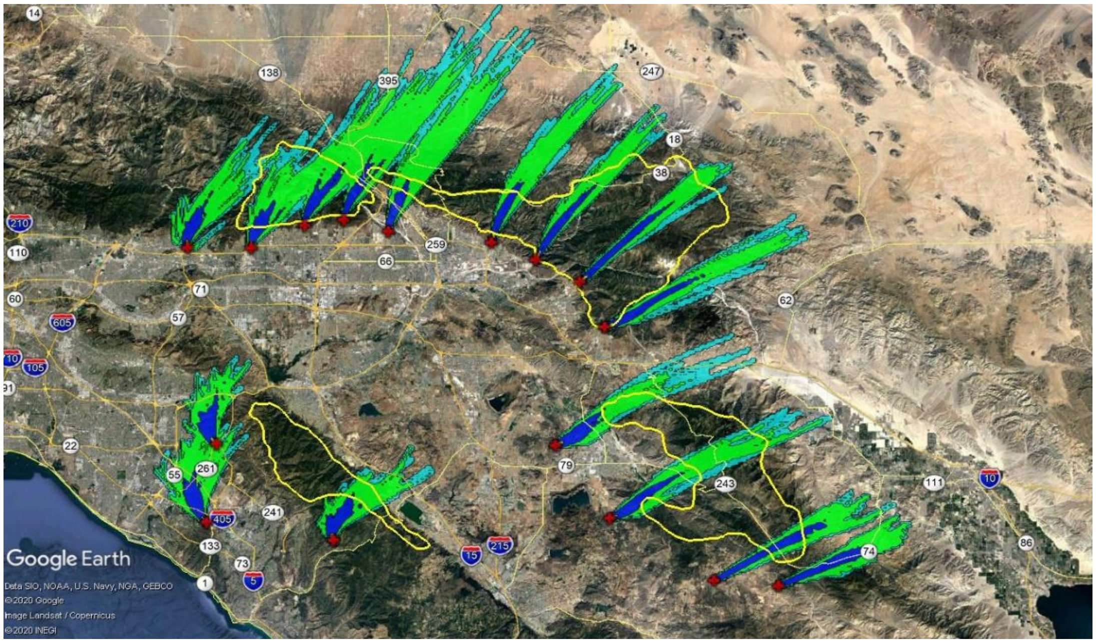

Figure D.6 Two-hour projected plume dispersion from all ground sites valid at 0500 PST on March 2, 2015.

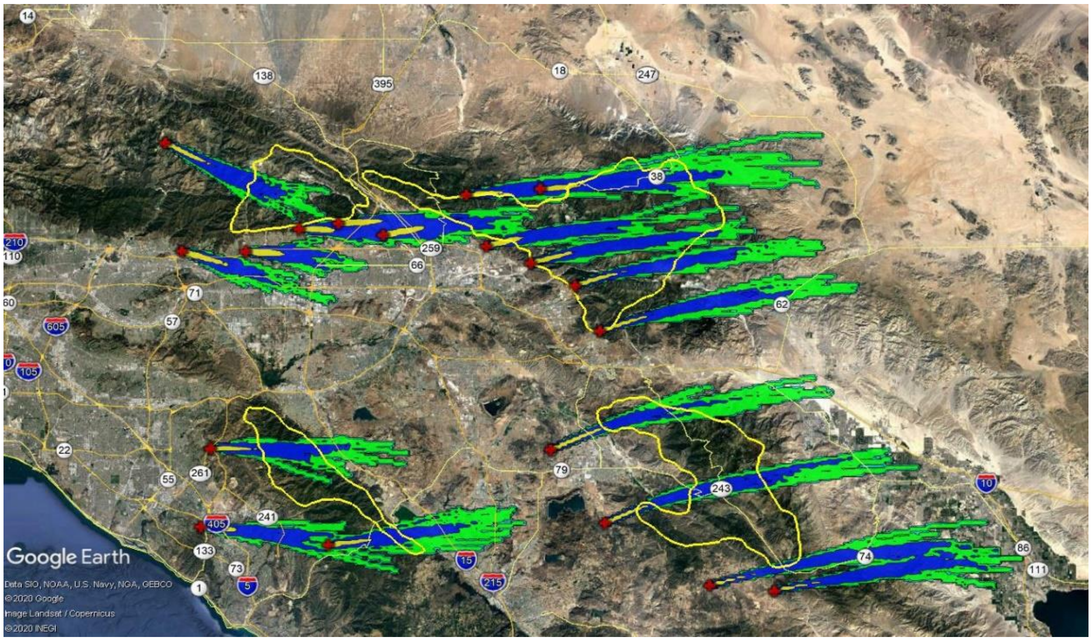

Figure D.7 One-hour projected plume dispersion from all ground sites valid at 0000 PST on December 14, 2015.

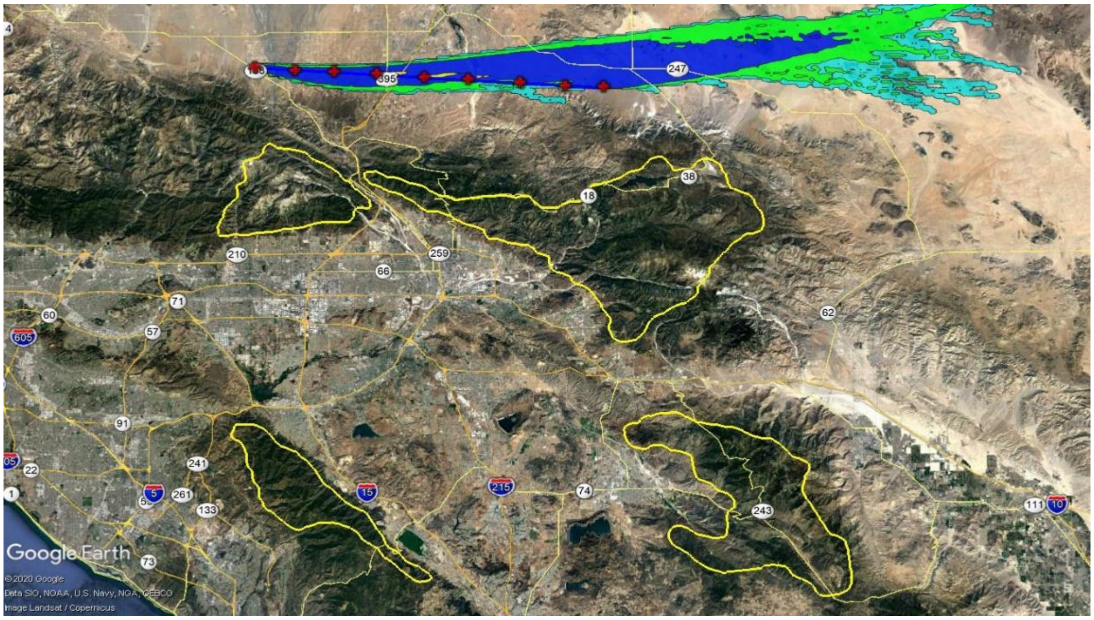

Figure D.8 One-hour projected plume dispersion from flight track at approximately 9800 feet above sea level, north of the NE target areas valid at 0000 PST on December 14, 2015. Note that plumes are remaining north of the area.

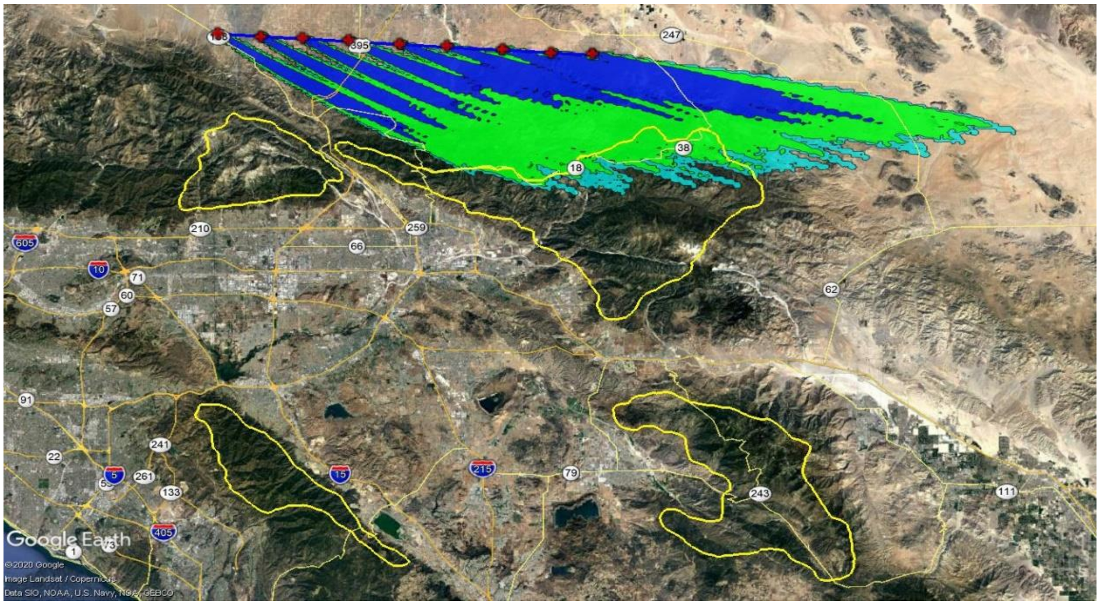

Figure D.9 One-hour projected plume dispersion from flight track at approximately 9800 feet above sea level, north of the NE target areas valid at 0300 PST on December 14, 2015. At this point, precipitation has ended across the area.

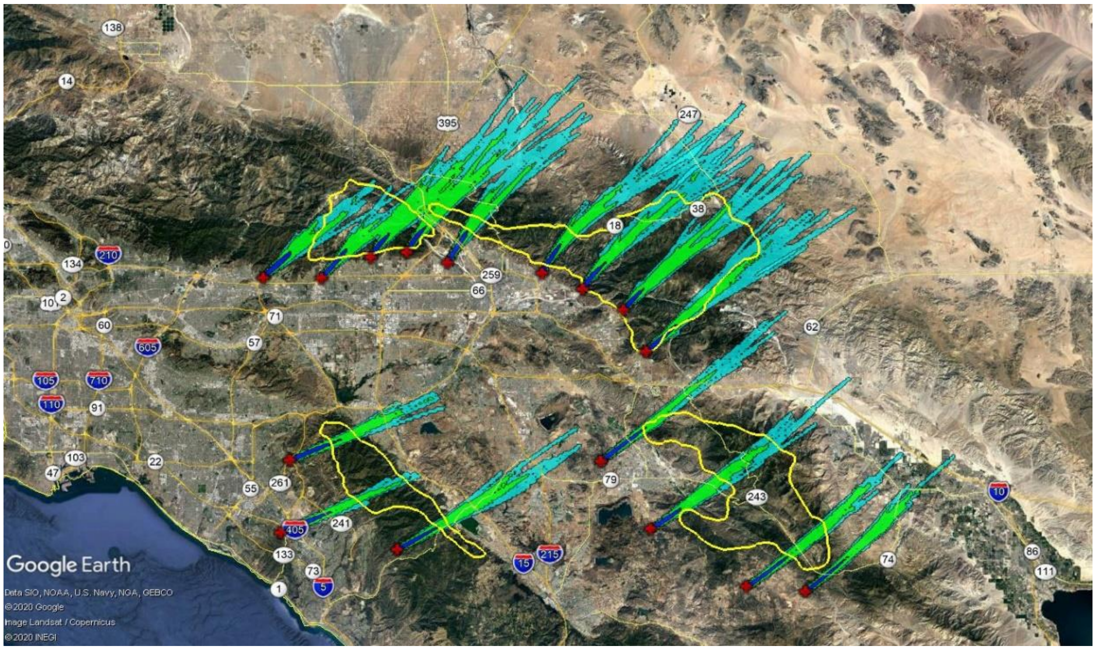

Figure D.10 One-hour projected plume dispersion from all ground sites valid at 1700 PST on January 6, 2016.

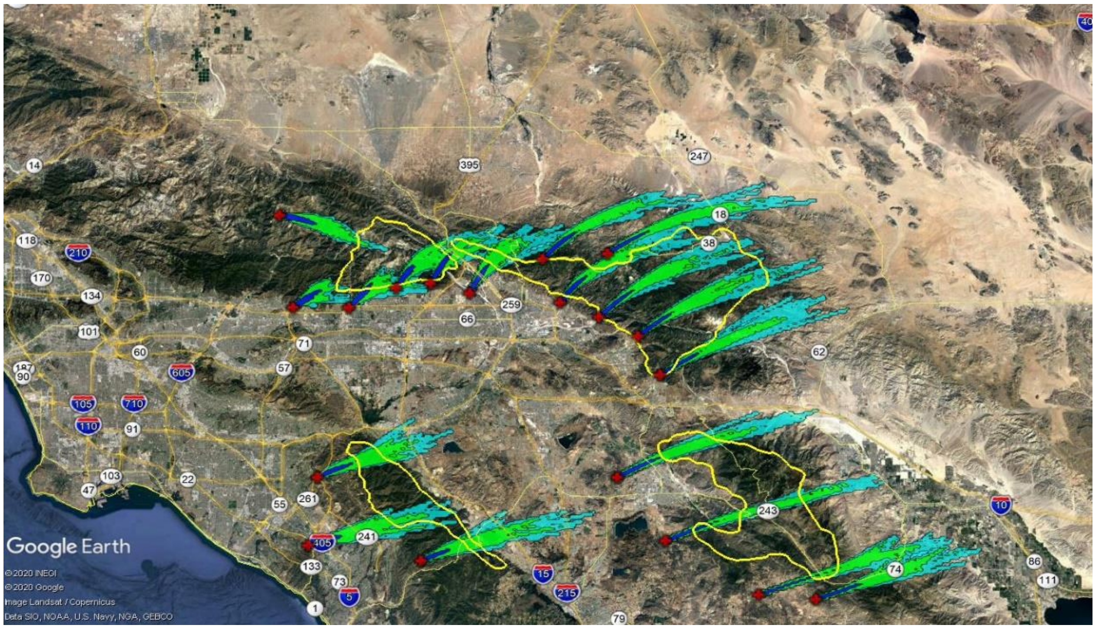

Figure D.11 One-hour projected plume dispersion from all ground sites valid at 0700 PST on December 24, 2016.

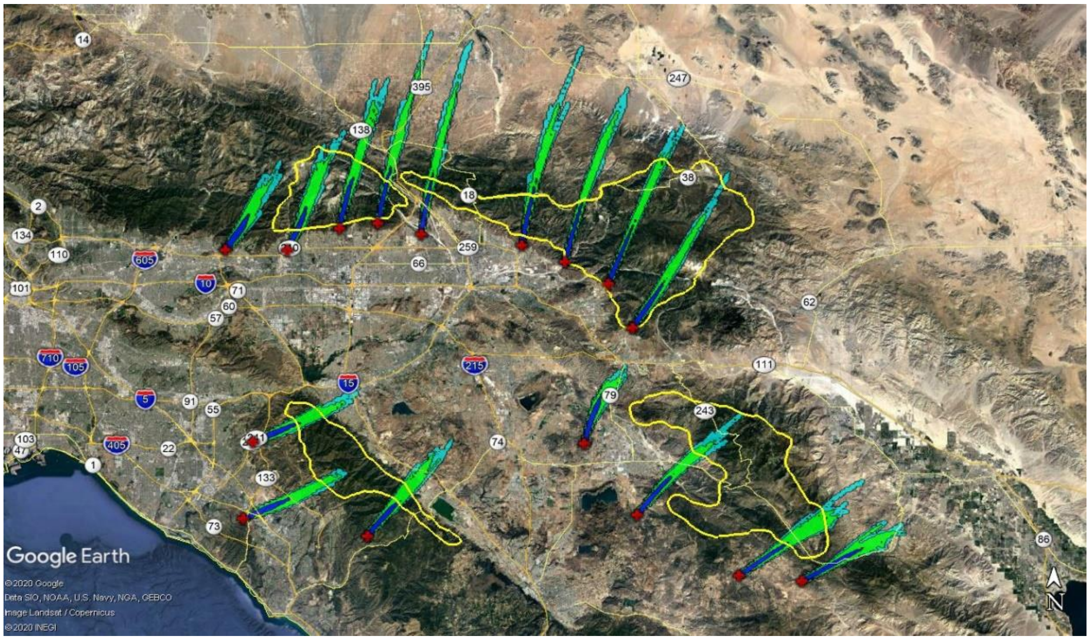

Figure D.12 One-hour projected plume dispersion from all ground sites valid at 0000 PST on February 27, 2018.

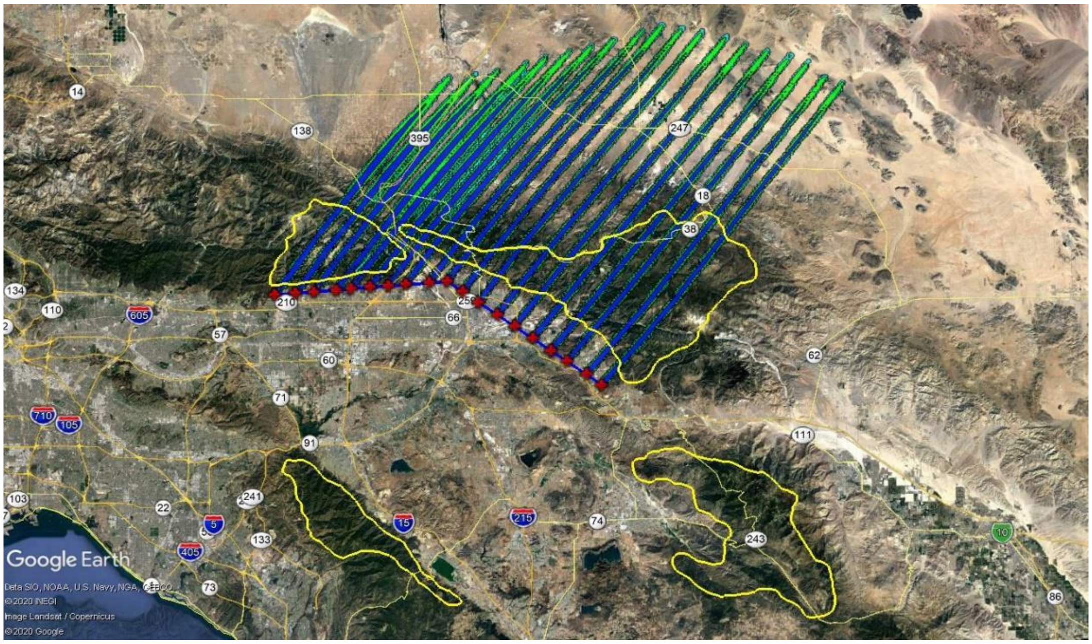

Figure D.13 One-hour projected plume dispersion from flight track at approximately 9800 feet above sea level, valid at 0100 PST on February 27, 2018.

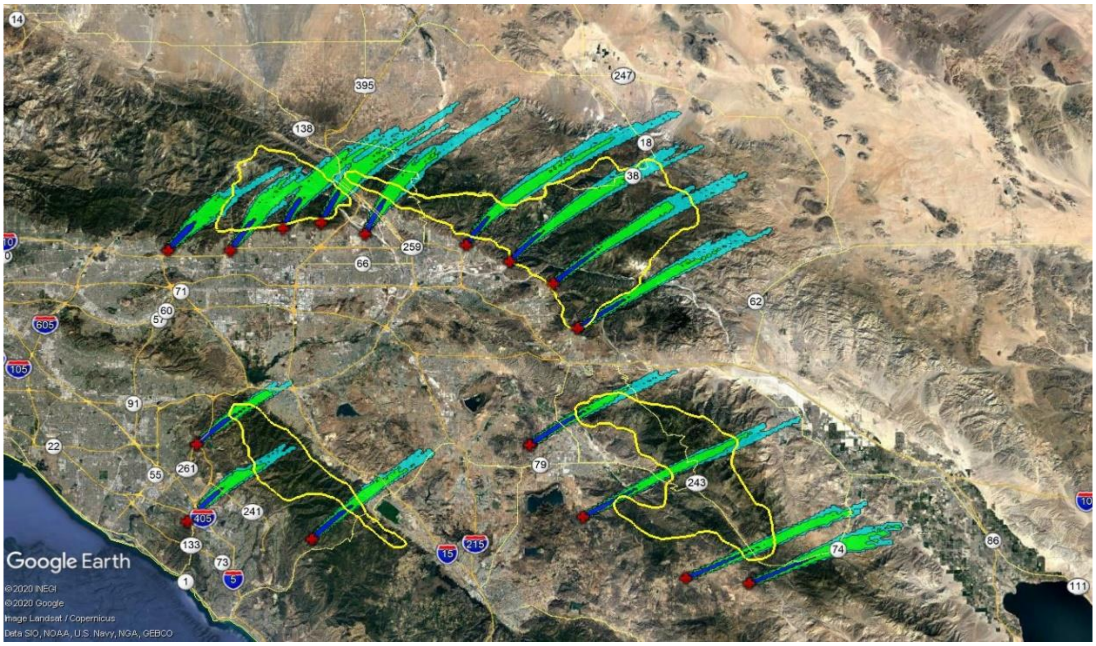

Figure D.14 One-hour projected plume dispersion from all ground sites valid at 0400 PDT on March 15, 2018.

APPENDIX E: ENVIRONMENTAL CONSIDERATIONS

Summary of Environmental Considerations

No significant environmental impacts are expected from cloud seeding programs that would be similar to the proposed SAWPA program. Indeed, published scientific literature clearly shows no environmentally harmful effects arising from cloud seeding with silver iodide aerosols (the proposed seeding agent for the SAWPA program) have been observed, nor would be expected to occur. Based on this work, silver iodide is environmentally safe as it is currently being used in the conduct of cloud seeding programs.

A summary of what is known regarding the items of potential interest is provided in the following.

Downwind Effects or Extra Area Effects of Cloud Seeding

Perhaps the most frequently asked question regarding the possible establishment of a cloud seeding program in an area that has not previously been involved in cloud seeding programs is: won't areas downwind of the intended target area experience less precipitation during the seeded periods? The answer to this question is no, based upon analysis of precipitation in a number of areas downwind of research and operationally oriented cloud seeding programs. In a review paper on this topic, Long (2001) provides information from a variety of both winter and summer programs.

An example of an analysis of potential downwind effects from an operational winter program is found in Solak et al. (2003). That paper examined the precipitation that fell in areas located in eastern and southeastern Utah and western Colorado, located downwind of a long-term winter program that has been conducted most winters since 1974 in the central and southern Wasatch Mountains of Utah. The abstract from this paper is as follows: *"Estimations of effects on precipitation downwind of a long-standing operational snowpack augmentation program in Utah are made, using an adaptation of the historical target/control regression technique which has been used to estimate the seasonal effects over more than twenty seasons within the program's target area. Target area analyses of December-March high elevation precipitation data for this program indicate an overall seasonal increase of about 14%. Estimations of downwind effects are made for distance bands downwind as far as 150 miles. The downwind analyses indicate increases of similar magnitude to those for the target, expressed as percentages or ratio values, extending to about 100 miles downwind. Beyond 100 miles the ratio values decay, reaching about 1.0 (e.g., no effect) at about 125 miles. Expressed as average-depth precipitation amounts, the target area precipitation difference is about 1.4 inches of additional water, while the values within downwind distance bands range from 0.4 to 0.25 inches, reaching zero at about 125 miles."*

DeFelice et al. (2014) summarized the available information on this topic. The following is the abstract from this paper:

> *"This paper examines the commonly-held hypothesis that cloud seeding reduces precipitation in regions adjacent to seeding target areas, sometimes referred to as "downwind" but more correctly referred to as "extra area" effects ("the robbing Peter to pay Paul" hypothesis). The overall concept in the potential creation of extra area effects from seeding is illustrated with respect to the hydrologic cycle, which includes both dynamical and microphysical processes. For the first time, results were synthesized from five operational and research weather modification experiments, including winter orographic snowpack enhancement and summer experiments to enhance rainfall.*

> *One of the most surprising aspects of these results is that extra area seeding effects on precipitation appear to be uniformly positive (5–15% increases, perhaps greater for some convective systems) for both winter and summer seeding projects examined in this paper. The spatial extent of the positive extra area seeding effects may extend to a couple hundred kilometers for winter orographic seeding projects and summer convective seeding projects (such as North Dakota, Texas, Thailand). Both microphysical and dynamical effects of seeding appear to be contributors to these extra area effects. Future work needs to incorporate larger data sets from some of the larger more sustained projects with advanced cloud models and tracer experiments".*

Toxicity of Seeding Agents

By far the most common seeding agent in use today for winter cloud seeding programs is silver iodide. The potential environmental impacts of silver iodide have been studied extensively. Klein (1978) in a book entitled "Environmental Impacts of Artificial Ice Nucleating Agents" concludes that

> *"The major environmental concerns about nucleating agents (effects on plant growth, game animals, and fish, etc.) appear to represent negligible environmental hazards. The more subtle potential effects of silver-based nucleating agents, such as their possible ability to potentiate the movement or effects of other materials of environmental concern, or to influence the activity of microorganisms in soils and aquatic environments after being bioconcentrated by plants, warrant continued research and monitoring. Effects, if they occur, are not expected to involve unacceptable risks. The long-term use of silver iodide and the confidence which the weather modification profession has in delivery systems and in the efficacy of this material, make it unlikely that other agents, with the exception of dry ice, will be used on a large scale, unless there are improvements in delivery systems and major changes in the economics of silver availability."* In the same book a summary of potential impacts on humans is presented as follows: *"The effects on humans of ingestion or topical contact with silver iodide used in cloud seeding can be considered negligible. Decade-long observations of cases (unrelated to cloud seeding) of ingestion of large silver doses revealed no physiological concern. In addition, surveys of seeding generator operators who have had long-term intensive contact with silver iodide reveal that they have not experienced medical difficulties."*

A report prepared by the Metropolitan Water District of Southern California (Ryan, 2005) contains the following summary on the topic of possible toxicity of silver iodide:

> *"There has been a concern about the toxicity of the most common cloud seeding material, silver iodide (AgI) on the environment. The typical concentration of silver in rainwater or snow from a seeded cloud is less than 0.1 micrograms per liter. The Environmental Protection Agency recommends that the concentration of silver in drinking water not exceed 0.10 milligrams per liter of water. Many regions have much higher concentrations of silver in the soil than are found in seeded clouds. Industry emits 100 times as much silver into the atmosphere in many parts of the country, and silver from seeding is far exceeded by individual exposure from tooth fillings. The concentration of iodine in iodized salt used on food is far above the concentration found in rainwater from a seeded storm. No significant environmental effects have been noted around operational programs, many of which have been in operation for 30 to 40 years (WMA, 1996)"*

The concentration of silver in rainwater or snow from a seeded cloud using the above information is on the order of 1000 times less than the EPA Standard.

Specific to silver concentrations in snowmelt water, Marler (2007) reported on lake water and sediment studies conducted for two long-term seeding programs operated by the Pacific Gas and Electric Company (PG&E) in the Sierra Nevada of California. Samples from a number of surface sites were analyzed for their silver content. The program areas are subject to moderate seeding material releases over periods of nearly fifty years, with annual amounts varying from 9-90 pounds for the Mokelumne area and from 45-180 pounds for the Lake Almanor area.

The report presented the following characteristics regarding silver iodide and silver chloro-iodide compounds used in cloud seeding:

- *"Have extremely low solubility in water*
- *Remain solid particles in air, cloud, precipitation*
- *Do not ionize to produce Ag+ under ambient environmental conditions*
- *Are not very bio-available in the environment*
- *Background Ag concentrations in Sierra snow < 2.0 ppt (ppt= g Ag/ml x 10-12)*
- *[Ag] in seeded snow typically range 40–60 ppt in layers sandwiched between unseeded snow.*
- *Total snowpack profile mean Ag concentrations average 5-20 ppt in highly effective seeding programs"*

Conclusions from the overall study include the following (from Marler, 2007):

- *"High resolution analysis of water, sediment and biological samples from areas subjected to long-term, 50 year+, cloud seeding programs, specifically PG&E's Mokelumne and Lake Almanor cloud seeding programs, support the following:*
- *The amount of silver iodide released to the atmosphere in cloud seeding is small, and even after many years of cloud seeding operations the resulting environmental concentrations very small to non-detectable.*
- *Given the stability of silver iodide compounds, extreme insolubility of silver iodide in water and the absorptions of ionic silver by colloids found in the sediments and aquatic vegetation, silver concentrations in the Mokelumne and Lake Almanor Basin from cloud seeding are expected to be minimal.*
- *Since the monitored levels are low, usually below the detection limit in the target watershed, it is unlikely that continued cloud seeding operations would result in any significant increase in silver concentrations in the target watersheds.*
- *Silver concentrations were below regulatory standards. Therefore, continued operations should not result in any significant chronic effect to sensitive aquatic organisms.*

- *There is little to suggest the silver from cloud seeding gets into the system and bio-accumulates in organisms."*

Also, worth noting is a statement by the Weather Modification Association in its formal position statement (WMA 2016):

> *"The published scientific literature clearly shows* ***no environmentally harmful effects*** *arising from cloud seeding with silver iodide aerosols have been observed, nor would be expected to occur. Based on this work, the WMA finds that silver iodide is environmentally safe as it is currently being used in the conduct of cloud seeding programs".*

A recent Mitigated Negative Declaration (MND), prepared by the Sacramento Municipal Utility District (SMUD) on their winter cloud seeding program in California (SMUD 2017), contains an appendix on the potential environmental effects of silver iodide. The following is the Executive Summary from this MND:

> *SMUD has conducted cloud seeding since 1968 in the South Fork American River watershed upstream of the Upper American River Project (UARP) over a 190-square mile target area, with a currently planned expansion to 444-square miles. Silver iodide (AgI) is a compound of silver used in cloud seeding activities to promote the formation of ice crystals and enhance total snowpack accumulation. Silver iodide is used for cloud seeding because its crystalline structure makes the compound ideally suited for ice formation, it exhibits very low solubility in natural waters (i.e., less than 1 microgram per liter [ug/L]), and it is not bioavailable or toxic to organisms in the environment.*
>
> *In general, studies of cloud seeding using silver iodide have demonstrated increased total silver concentrations in associated precipitation, but no corresponding, statistically significant systematic increase or accumulation of total silver in freshwater, soil, or in stream, lake, or reservoir sediments in the areas experiencing cloud seeding.*
>
> *Silver iodide is not typically measured in isolation in the environment, with existing analytical methods relying upon measurements of total silver. Cloud seeding using silver iodide has been found to increase total silver concentrations in precipitation between two and three times on average when compared to unseeded precipitation.*
>
> *In studies conducted in the California Sierra Nevada, total silver concentrations in snow from areas seeded with silver iodide were typically less than 0.02 ug/L but reached a maximum of approximately 0.115 ug/L. Freshwater total silver concentrations in areas cloud seeded with silver iodide were usually less than analytical detection limits (between 0.0005 and 0.04 ug/L depending on the method used), but they were occasionally measured between 0.09 - 0.74 ug/L in the Feather River-Lake Almanor watershed and less than 0.0005 ug/L on average in the Mokelumne River watershed. In general, total silver concentrations have not been shown to increase above background levels in terrestrial, stream, and lake sediments in areas seeded with silver iodide.*
>
> *There are no documented environmental hazards associated with silver iodide and to date no studies have identified adverse environmental impacts due to cloud seeding with silver iodide. There are no federal, state, or local regulations establishing acceptable levels of exposure for silver iodide. In natural waters, silver iodide has such extremely low solubility (0.984 ug/L) that it is generally considered to be insoluble and is thus not bioavailable or toxic.*

In contrast, there are known environmental hazards and regulations associated with dissolved silver (free silver ion [Ag+]) because, unlike insoluble silver iodide, dissolved silver is bioavailable and potentially toxic to sensitive organisms. Dissolved silver is a negligible environmental hazard for humans, but federal and state regulations set the maximum contaminant level for dissolved silver in drinking water at 100 ug/L to prevent a cosmetic gray or blue-gray discoloration of skin that may occur from chronic exposure to high levels. Dissolved silver is a potential hazard to aquatic and terrestrial organisms at a wide range of concentrations depending on the species, life-stage, and water hardness with 1.2 to 4.9 ug/L lethal to sensitive aquatic organisms. Accordingly, the USEPA has set an acute freshwater criterion or criteria maximum concentration (CMC) for dissolved silver as a function of water hardness with a CMC of 3.2 ug/L at a hardness of 100 mg/L. Lower water hardness results in a lower CMC for silver. There is no chronic freshwater criterion for dissolved silver. Dissolved silver also is an environmental hazard to terrestrial plants and animals, but the concentrations causing adverse effects are much higher than found under typical natural conditions. However, despite the hazards associated with dissolved silver, there is no equivalent hazard with silver iodide because it is insoluble and thus not bioavailable.

Historically, SMUD has measured total and dissolved silver in water samples within the Upper American River watershed at various times. Total silver would include any contributions from silver iodide, while dissolved silver would not include any silver iodide since silver iodide is insoluble in water under natural conditions. Measurements of total silver, including both dissolved and particulate silver, in all years ranged from <0.008 – 0.86 ug/L, which in all cases is below the USEPA secondary drinking water threshold (100 ug/L dissolved silver). Dissolved silver was analyzed in 2004 and ranged from<0.0045 – 0.02 ug/L with the hardness-adjusted freshwater CMC for aquatic biota being exceeded in two reservoir samples and one riverine sample. Total and dissolved silver concentrations in water and fish tissue measured more recently have been consistently at or near the lowest analytical detection limits.

SMUD currently monitors total and dissolved silver in the Upper American River watershed every five years as part of a suite of trace metals. Monitoring is conducted seasonally at 22 sites across seven stream reaches and 20 sites across 11 reservoirs in the watershed, where monitoring sites range in elevation from approximately 500 – 6,500 feet, covering the full elevational extent of SMUD cloud seeding activities. Of the 42 total riverine and reservoir monitoring sites, 23 are located directly within the existing 190-square mile cloud seeding target area, and the remaining sites are located downstream of both the existing and the expanded target area, allowing for an assessment of potential downstream transport of silver. The current trace metals monitoring program would detect long-term seasonal trends in total and dissolved silver concentrations in specific reservoir and river locations within the existing cloud seeding target area, and it would also detect spatial variations in concentrations within this area (e.g., particular locations that may exhibit higher concentrations than others). While the frequency and spatial coverage of the current monitoring program is not able to attribute variations in concentrations of these forms of silver to individual cloud seeding events, it would measure long-term changes in the amount of dissolved (i.e., bioavailable) silver directly within the existing 190-square mile cloud seeding target area, and downstream of both the existing and the expanded target area, which could be compared to long-term trends in SMUD application rates of silver iodide.

Potential Environmental Impacts of Winter Cloud Seeding

Many of the environmental impact studies on wintertime programs were performed on programs designed to increase snowpack in mountainous areas of the western United States. Most of these studies were funded under the Bureau of Reclamation's "Skywater Program". Four programs of note concerned with wintertime programs were:

- Potential Ecological Impacts of Snowpack Augmentation in the Uinta Mountains, Utah. A 1981 report from Brigham Young University authored by Kimball Harper (Harper, 1981) summarizing the results of a four-year study.
- Ecological Impacts of Snowpack Augmentation in the San Juan Mountains, Colorado. A 1976 report edited by Harold Steinhoff (Colorado State University) and Jack Ives (University of Colorado) summarizing the results of a five-year study (Steinhoff and Ives, 1976).
- The Medicine Bow Ecology Program. A 1975 report on studies conducted in the Medicine Bow Mountains of southern Wyoming (Knight, 1975).
- The Sierra Ecology Study. A five-volume report summarizing work on possible impacts on the American River Drainage in California (Smith et al., 1980).

In general, the findings from these studies were that significant environmental effects due to the possible conduct of cloud seeding programs in these areas were not expected to occur. A couple of examples that support this conclusion are as follows:

A statement made in the final report on the San Juan Mountains program (Steinhoff and Ives, 1976): "The results of the San Juan Ecology Program suggest that there should be no immediate, large-scale impacts on the terrestrial ecosystems of these mountains following an addition of up to 30 percent of the normal snowpack, but with no addition to maximum snowpacks. Further, much of the work reported here suggests that compensating mechanisms within the study's ecosystems are such that any impacts would be buffered, at least for short periods of time, and of lesser magnitude than the changes in snow conditions required to produce them."

The Bureau of Reclamation published an "Environmental Assessment and Finding of No Significant Impact (Harris, 1981) for the Sierra Cooperative Pilot Program. Quoting from the introduction of this report:

> *"This document and the program environmental assessment serve as the basis for determination that no further action is necessary to comply with the National Environmental Policy Act of 1969 (Public Law 91-190) for the following reasons:*
>
> *1) The Sierra Cooperative Pilot Program Environmental Assessment examines a research program designed to seed, on a randomized basis, some of the cloud types which occur within winter storms in the Sierra Nevada of California and Nevada. The increase in annual precipitation expected from seeding all eligible storms during an average or less-than-average year would be 10 to 15 percent. The annual precipitation increase expected from randomized seeding of selected cloud types would be 5 to 7.5 percent. The report analyzes the potential effect of these increases upon weather elements, hydrologic and physiographic phenomena, plant and animal communities, the human environment, and land and water resource use in the program area. It*

also discusses possible impacts of the seeding agents, dry ice and silver iodide. The report concludes the research program will not result in significant or adverse effects upon the environment.

2) *Consultation with Federal and State agencies has resulted in the determination that this program will not affect endangered or threatened species of plants or wildlife or their habitats in a significant or adverse manner.*
3) *Archeological and historic sites and sites of extraordinary aesthetic value will not be significantly or adversely affected by the program.*
4) *Program activities and resultant increases in precipitation will not affect the human environment, lifestyle, or existing land and water resource use in a significant or adverse manner. The program design includes suspension criteria to prevent operations during periods that would lead to public safety hazards."*

The American Society of Civil Engineers published a Manual 81 on Engineering Practice, entitled *Guidelines for Cloud Seeding to Augment Precipitation* (ASCE 2016). A section of that publication addresses environmental issues relating to weather modification. A key summary paragraph from Manual 81 is quoted below.

> *"The essence of the results is that changes that might be expected in the environmental factors (1) were most often subtle, nil, or indiscernible in relation to other natural influences (e.g., effects of fire or insects on forest vegetation); (2) would be of the same type and magnitude as would result from a sustained increase of a corresponding percent(age) in natural precipitation (e.g., as a gradual change in herb species composition might occur in a wetter climate); (3) might be beneficial as often as not and depending on point of view (e.g., as when fish habitat increases with lake level); and (4) would have net outcomes that strongly affect ecosystem management practices (e.g., as when increased weed growth and grassland productivity occur together). During the 1970's, seeding agents, chemical complexes of silver iodide, were examined for ecological effects (Cooper and Jolly, 1970; Klein, 1978). Conclusions from those studies point to little or no effects on terrestrial or aquatic biological communities, either immediately or after many, many years of silver iodide application in the small dosages possible from cloud seeding (Reinking et al., 1995)."*

A more recent U.S. Bureau of Reclamation Environmental Assessment (EA) was completed in 2010 (BUREC 2010) for an operational winter cloud seeding for the Walker River Basin in Nevada. Based on the analysis of the environmental impacts as described in the EA for the Walker River Basin Cloud Seeding Project, Reclamation has determined that the proposed federal action will not significantly affect the quality of the human environment, thus an environmental impact statement is not required. This Finding of No Significant Impact (FONSI) is supported by the *Environmental Assessment for the Walker River Basin Cloud Seeding Project.*

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APPENDIX F: QUESTIONS & ANSWERS

NAWC compiled the questions asked via email or during a live zoom meeting

Emailed Questions:

Question 1

Throughout the Task 3 report there were multiple changes to the location, number and type of ground seeding sites compared to the previous report. Additionally, the airborne program was revised to remove the NW target area. Given the significant changes to the number and location of the land-based generation stations and to the aerial flight path from the previous report, we find it critical to see how these modifications impact the "Estimated Precipitation and Streamflow Increases" table on page 27 of the Task 1 & 2 Report. These program changes, in addition to the newly outlined cloud seeding suspension criteria, could reduce the estimated precipitation and streamflow resulting from a weather modification program.

Answer

Changes and adaptations were made after careful scrutiny and consideration. The sites that were removed after one of two manifestations:

- Redundancies were noticed, where plumes overlapped more than necessary. -or-
- Seeding plumes were shown, through additional study, to impact areas outside of the watershed.

We do not believe any of these changes would significantly alter the overall impact of the program. We also determined, during this phase of research, that it would be more beneficial to run a smaller network of generators with a higher concentration of solution than to operate a redundant network, with a lower concentration of solution. The generators that were removed had the highest propensity of releasing seeding agents that were diverted by winds outside of the watershed.

These design changes reflect a careful analysis of both the technical (equipment based) feasibility of the program as well as the economic feasibility.

Question 2

The primary benefit of weather augmentation to OCWD would be an increase in runoff amount that arrives at Prado Dam. This streamflow is most accurately measured by the USGS gauging station 11074000 commonly referred to as 'Santa Ana River Below Prado Dam'. It is uncertain how much of the projected increased precipitation and resultant streamflow from weather augmentation would reach Prado Dam. If modeling work is available that indicate the projected increase in runoff at the aforementioned USGS gauging station, OCWD would like to see this information.

Answer

We would encourage you to perform modeling to demonstrate the impact downstream of augmented upstream runoff. We do not perform this type of modeling, but could work with an engineering firm to get them accurate estimates on stream flow increases at metered locations in the river network.

Question 3

The manner in which dams are operated on Santiago Creek affects how much water OCWD receives for groundwater recharge. With weather augmentation, Santiago Creek would likely provide limited measurable benefit to OCWD from weather augmentation due to dams upstream of OCWD's recharge facilities on the Santiago Creek. However, we are interested in learning if targeting the SW area could increase precipitation in the low-lying areas further inland beyond the Santa Ana Mountains. If there is insignificant precipitation increases on these low-lying areas, then removal of the SW target area may be warranted.

Answer

Cloud-seeding to enhance rainfall in the SW target area, will definitely have an impact in the more inland areas to the east of the target area. Though we were initially concerned about this "down wind" affect, it became immediately apparent that a number of SAWPA members have a vested interest in water that falls in this area. We have worked carefully to determine when the down-wind affects may produce flooding conditions in these areas, and when they would prove beneficial to the watershed. This is discussed in our conversation on "Suspension Criteria."

Question 4

In light of the recent wildfires started by a firework type device can you clarify this phrase in the text?

> *"Airborne seeding operations are coordinated between the project meteorologist and the seeding pilot using VHF frequency 122.85. Wing-mounted flare racks containing silver iodide flares will be used, with flares burning over a 4-5-minute period, producing plumes of ice nuclei upwind of the target area. Each flare contains 16.2 g of silver iodide."*

Answer

The flares that will be used are "burn-in-place" flares, meaning the flare never leaves the wing of the plane, or the tower of the AHOGS system. At the elevations that seeding aircraft fly, any possible embers from the flares will extinguish long before they hit the ground. The AHOGS systems use specialized spark arrestors to catch the embers and prevent them from hitting the ground around the tower installations. In addition, weed abatement is performed to prevent weeds or grasses that could serve as fuel, from encroaching on the towers. Our towers are also equipped with high-resolution cameras, that are used during the illuminating of flares. If a fire ever did occur, we would be able to notify local fire authorities immediately. These systems have been in use (with or without cameras) for almost 30 years, without any issues in California.

Question 5

The enhancements to seasonal rainfall were shown to be about 0.5” on the target areas. The average seasonal rainfall for most targeted areas (mountainous areas) is probably 25”. What would we expect the enhancement over the urban/suburban valleys to look like where seasonal rainfall is much lower (9-12”)?

Answer

High elevation mountainous areas will experience higher rainfall than lower elevation sites, the increase estimates that were provided should be taken to represent the increase expected in the target area as a whole, with increases at higher elevation expected to be (in some cases) significantly higher. The expected increase over populated areas is projected to be dramatically lower, as they are not a primary target for any of the generators. The largest increases would be for areas downwind from the AHOGS in the South West area.

Question 6

Will suspension criteria impact the effectiveness of the seeding program?

Answer

NAWC understands that suspension criterium are critical to the safety and positive public perception of a weather modification program. NAWC also understands that suspending seeding activity reduces the potential impact of the program. When the issues are weighed carefully it is possible to have a highly effective and very safe program. In determining when to recommend suspending operations we addressed each of the four target areas differently, based on their locations, proximity to populations, infrastructure, propensity of flooding and probable down-wind affects. We determined that the South West target area required special consideration, after carefully discussing the down-wind areas with the Riverside County Flood Control and Water Conservation District. In the end we recommended elevated suspension criteria for this location. These criteria however, target the most severe of storm events, those most likely to overwhelm infrastructure and result in localized flooding or flash flooding. They are based on precipitation levels that typically only occur once every 2-3 years (a one in 2-year event). Probability would indicate that we would only miss 1 event every two years due to flooding concerns, which would have only a marginal impact on the overall program effectiveness. In addition, we would likely seed these events for the other 3 target areas during these storm events.

Questions from Presentations

Question 1

Are these estimated increases derived from an assumption of average rainfall over the target areas?

Answer

The average rainfall is determined by averaging values at the available precipitation stations. This is why the first part of this feasibility and design study is so critical. Understanding the climatology of the region plays a critical role in estimating the success of a program.

Recall that the average was not derived from the most recent five seasons. To ensure that the program would be cost effective even if there were dry years mixed in with average years, five non-continuous seasons from the past 10 historic years were observed. These five selected seasons were selected to represent a modified average that would more accurately represent the benefits of seeding during naturally occurring “dry,” “normal” and “wetter” years.

Question 2

Why are AHOGS used in Orange County versus the CNGs used elsewhere?

Answer

AHOGS release a very high concentrated amount of Silver Iodide, in a short period of time. These devices are used in coastal areas where liquid water concentrations are high and there is a lot of turbulence (strong updrafts) due to the passage of convection bands that loft the and quickly mix the Silver Iodide seeding material into the convection bands.

These systems are more expensive than traditional ground generators, and are therefore used sparingly where the benefit outweighs the added investment.

Question 3

Will the benefit from the AHOGS extend beyond the SW target area into the lowlands between the target areas?

Answer

Yes, the benefits of the AHOGS will be extended through the areas downwind, including the wetlands (see discussion on Downwind Effects in Appendix E). Many members have expressed interest in additional water and runoff in these areas. We will work with the Riverside County Flood Control and Water Conservation District to set up suspension criteria to help ensure that these downwind effects do not augment major flooding events.

Question 4

Discussion about Atmospheric Rivers (ARs) bringing significant amounts of annual precipitation to the area, discussion about the “AR Scale from 1-5;

Answer

Large precipitation events associated with Atmospheric River Events, are generally self-sufficient and large rainfall producers. These hyper productive storms are generally not seeded since they are assumed to be naturally efficient in producing precipitation. When the projected increases from a Weather Modification program were calculated, estimated increases were only applied to storms we deemed seedable. Storms of this nature were not generally considered seedable, meaning no increase for these storms was calculated.

Question 5

How are operations handled in areas where recent wildfires risk abnormally high debris flows?

Answer

When large fires occur, an experienced weather modification contractor will work closely with flood districts to determine the best approach for the season or seasons following the fire. Fires often necessitate slight to moderate adjustments to suspension criteria in affected areas of the program. Occasionally fires will instigate a long-term suspension of seeding activity in the regions most impacted by the burn. The Santa Ana River Watershed consists of 4 separate “target areas,” which are fairly well isolated from each other, and all targeted during different wind regimes. NAWC does not envision a wildfire burn area in one target area that would necessitate the cessation of seeding in the other three target areas.

It is critical that the contractor hired to perform this work, have significant experience working in areas that have experienced wildfires.

Question 6

Can you please explain the benefits of placing generators on public land vs private land?

Answer

There are a lot of benefits to using public land. The program is insulated from change as private land ownership can change, and landowners may lose the ability or willingness to operate seeding equipment. Often permits will be required when operating on public land, but these permits are generally inexpensive and the Cloud Seeding Contractor should perform the majority of labor involved with obtaining the permits (creating the image files and documentation). Stability is the biggest gain with operating off public land.

Question 7

How was the value of $255/acre-ft determined, as this value is likely much lower than the actual cost of water for many agencies in the Santa Ana Watershed?

Answer

NAWC agrees that $255 is on the lower end of estimates received by member agency staff. However, using a number lower than the actual value of untreated, unpressurized water, ensures that we don’t overvalue the program. $255/ac-ft proved valuable enough to more than justify a program of sufficient design and complexity to optimize results.

Question 8

Could the SNOWIE results, from a research program conducted in Idaho, be replicated in the Santa Ana River Watershed?

Answer

If there is funding to bring in the equipment necessary to track and measure the effects of seeding, then by all means something could be done.

Question 9

Will increasing snowpack in the upper head-waters benefit Orange County?

Answer

We found that increases in precipitation in the Santa Ana River Watershed yield a roughly 1.15 multiplicative factor on stream flow. In other words, a 10% increase in precipitation will yield a 15% increase in streamflow. Water ways are generally more efficient when more runoff is present, as a smaller percentage of the augmented runoff is lost to soil absorption. We thus predict a positive impact down the entire stream/canal network in the Santa Ana Watershed. What NAWC cannot comment on, is how water rights are negotiated in the network, and who ownership of the surplus runoff will belong to.

In NAWC's first presentation to a consortium of SAWPA member employees, NAWC discussed programs in Utah and Colorado that are sponsored by the Lower Colorado River Basin States (Nevada, California, Arizona and New Mexico). These "Lower Basin States" contribute significant resources to weather modification programs 600 miles upstream from where the water will be used.

Question 10

Will the flight path, as presented be problematic due to its proximity to the Ontario International airport?

Answer

NAWC agrees, even with the limited flight path proposed in our updated program design, there could be significant pushback from the Ontario and other airports in the region. We reaffirm that getting flights of the desired nature approved for this program will be a complicated endeavor. We are well acquainted with the process of receiving the correct flight waivers and working with all the necessary parties to get the program approved. The permits and approvals, are not our biggest concern. The decision to allow a seeding aircraft to occupy the same airspace for an extended period of time, during intense storm activity, lies largely in the hands of air traffic control. With all the proper permits, waivers and licenses, a plane may still be grounded during critical seeding periods, if the tower is concerned about air traffic, or if the pilot is concerned about the safety of the flight.

Question 11

How long does an MND usually take to draft?

Answer

The MND process can easily take 6-12 months depending on whose working on it, and the amount of resources that are able to be dedicated to the project. The preparation of an MND could be contracted to a separate entity. It is also possible, and recommended, to begin the RFP process for the cloud seeding program during the later stages of the MND process.

Question 12

To the best of your knowledge has NAWC (or any other weather modification contractor) ever had any liability issues when it comes to seeding operations.

Answer

In order to protect against claims that cloud seeding contributed to hazardous conditions caused by storms, it is mandatory that the cloud seeding program has established comprehensive suspension criteria. Such criteria would indicate when seeding should be terminated or not initiated during certain storm events.

In addition, it is recommended that the selected cloud seeding contractor carry liability insurance with an important caveat:

> *"Sponsors shall request weather modification service contractors to provide liability insurance against the effects of operations."* (ASCE 2017, section 3.6.1)

This special insurance is termed **"consequential loss insurance"** and is normally not part of ordinary liability insurance". Depending on how this insurance policy is written, it may pay for legal defense costs if a lawsuit is filed against SAWPA or the contractor charging that the cloud seeding contributed to damages caused during a seeded storm or storm sequence.

It is also recommended that SAWPA require their selected contractor to name each of its agencies "additional insureds" to their "consequential loss" policy.

Details on the previous history of liability and lawsuits in the United States regarding claimed damages from cloud seeding is provided in section 3.4.1 of ASCE's publication entitled "Guidelines for Cloud Seeding to Augment Precipitation, Third Edition (ASCE 2016).

APPENDIX G: CLIMATE CHANGE

NAWC Inc, was hired to conduct a feasibility study to determine the effectiveness of a weather modification program to enhance rainfall in the Santa Ana River Watershed. Though NAWC Inc has a team of highly accomplished meteorologists NAWC is not a climatological firm and do not specialize in long term climate shift forecasting or modeling. NAWC is, however, very much aware of a number of climatologically related questions that often arise in conjuncture with climate change. The most significant of these issues are as follows, and will be addressed sequentially:

- Does cloud seeding for rain enhancement cause or contribute to climate change?
- How are cloud seeding programs adjusted to accommodate for climate change?
- Can cloud seeding help mitigate against the threats of climate change?

Potential Impacts of Cloud Seeding

Let us consider the long term, and more specifically the potential climatological impacts of weather modification for rain enhancement. Cloud seeding generators burn seeding agents in a solution of Acetone. The seeding agents themselves have no known impact on climate change, the only source of potential impact to climate change would be in the solvent and in the fuel. The solvent is Acetone (C3H6O). During combustion this solvent decomposes into 3H2O molecules and 3CO2 molecules. Carbon dioxide is a known “greenhouse” gas. Similarly, the primary fuel source, propane (C3H8), decomposes into carbon dioxide and water (3CO2 molecules and 4H2O molecules per molecule of propane). These two-combustion processes are much more efficient (less CO2 released per molecule of solvent or fuel), than with other combustion sources. As an example, common automobile fuel releases 8CO2 molecules per molecule of fuel. In addition to their chemical efficiency, both Acetone and Propane are used in such small amounts, the output of CO2 from an entire program over the course of a season is likely less than the output from one vehicle operating in the LA Basin for a single year. This makes the contribution of cloud seeding to climate change extremely insignificant and, for all intents and purposes entirely negligible.

Program Adaptations

A cloud seeding program is designed based on a number of climatological considerations and weather patterns. As climate change occurs, a number of these critical variables may gradually shift rendering the current design less effective. It is important that a weather modification operator remain aware of climatological trends and shifts and be prepared to modify the program design as necessary. During the 2020 calendar year NAWC has been working on an 8-month long research program to re-assess the climatology of one of our program areas and adapt our program accordingly. This labor-intensive process was commissioned in order to maximize the effectiveness of a seeding program that has been in place for over 3 decades. NAWC is analyzing temperature patterns, wind patterns, precipitation trends and other variables critical to cloud seeding, and using this data to improve our design. All weather modification programs should be assessed after their first 3-5 years of operation and annually after that point. If multi-year trends point to diminished returns, a more in-depth climatological review should be commissioned to determine appropriate responses to these climate shifts. Evaluation methods and practices are a critical measure of the aptitude of a weather modification provider, and should be considered carefully during an RFP phase.

Helping to Adapt to a Changing Climate

In considering the potential for weather modification to help mitigate against climate shifts, it is important to first consider the long-term climatological forecasts for the area in question. As stated above, NAWC does not produce independent long-term climatological forecasts, NAWC is however familiar with and subscribe to a number of resources that provide long term climate change predictions. In general, most long-term models predict hotter, drier conditions in the U.S. Continental Southwest, including those areas in and around the Santa Ana Watershed. This shift is predicted to increase current strains on already limited water resources. Cloud seeding for rain or snow augmentation may be an effective way to mitigate against these changes. NAWC estimated an 8-11% increase in rainfall resulting from a well-executed cloud seeding program. This increase in storm productivity could play a significant role in coping with the negative consequences of climate change on the Santa Ana River Watershed.