RESULTS FROM A WINTER CLOUD SEEDING FEASIBILITY/DESIGN STUDY CONDUCTED FOR THE LOPEZ LAKE AND SALINAS RESERVOIR DRAINAGE BASINS IN SOUTHERN SAN LUIS OBISPO COUNTY, CALIFORNIA

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ABSTRACT

North American Weather Consultants (NAWC) was contracted in 2016 by the San Luis Obispo County Flood Control and Water Conservation District (District) to conduct a feasibility/design study for a winter cloud seeding program to target the Lopez Lake and Salinas Reservoir (LLSR) drainage basins located in southern San Luis Obispo County, California. Recommendations from the American Society of Civil Engineers (ASCE 2016) publication entitled “Guidelines for Cloud Seeding to Augment Precipitation” were followed in determining that the proposed project was both technically and economically feasible. NAWC reviewed available information, compiled and analyzed data, and then developed a proposed program design. Regression relationships were established between November through April precipitation and annual runoff into the two target reservoirs. Estimated increases in precipitation of 9% or 17%, from an analysis of the long-term effects of an operational cloud seeding program conducted by the Santa Barbara County Water Agency in an adjacent drainage were inserted into the regression equations to estimate average increases in inflow to the two target drainages. The District provided NAWC with estimates of the value of this augmented runoff. The costs of conducting a seasonal cloud seeding program were estimated. These steps provided data that could be used to estimate benefit to cost ratios. NAWC concluded that the proposed program was both technically and economically feasible based upon ASCE 2016 criteria.

1.0 INTRODUCTION

The San Luis Obispo County Flood Control and Water Conservation District (District) contacted North American Weather Consultants (NAWC) in February 2016 about the possibility of NAWC performing a feasibility/design study for a winter operational cloud seeding program to target the Lopez Lake and Salinas Reservoir (LLSR) drainages located in southern San Luis Obispo County, California. NAWC submitted a proposal to the District and then was contracted to perform this work.

The stated goal of this program would be to augment the natural precipitation that occurs in the target area to provide additional inflow into these two reservoirs. Figure 1 provides the location of the proposed target areas.

NAWC followed the ASCE 2016 “Guidelines for Cloud Seeding to Augment Precipitation” in the performance of this work. A final report was submitted to the District in March 2017. The following sections of this paper summarize the work performed.
2.0 BACKGROUND

Recommendations from the American Society of Civil Engineers (ASCE 2016) publication entitled “Guidelines for Cloud Seeding to Augment Precipitation” include the following:

1. “When possible, the feasibility study for a program should draw significantly from previous research and well-conducted operational programs that are similar in nature to the proposed program (e.g., similar topography, similar precipitation occurrences, etc.).”

2. “The primary purpose of the feasibility study is to answer two questions. First, does it appear that a cloud seeding program could be implemented in the intended target area that would be successful in achieving the stated objectives of the program? Second, are the estimated increases in precipitation expected to produce a positive benefit-cost ratio?”

As suggested in #1 in the above, the design of the program draws heavily from a successful operational program that has been conducted for Santa Barbara County since 1981, which in turn was based upon the statistically significant positive effects observed in the Santa Barbara II research program conducted from 1967-1974 (Elliott, et al., 1971), (Thompson, et al., 1975), (Griffith, et al., 2005).

The Santa Barbara II research program, funded by the Naval Weapons Center, China Lake, California, consisted of two primary phases. Phase I, 1967-1971, consisted of the release of silver iodide by burning silver iodide impregnated flares from a single ground location (elevation near 2,500 feet MSL) located in the Santa Ynez Mountains northwest of Santa Barbara. These silver iodide flares were ignited as “convective bands” passed overhead. Convective (or convection) bands, somewhat similar to summer squall lines, had previously been found to be a common component of winter storms that impacted Santa Barbara County (Elliott and Hovind, 1964). 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 over the county. It is common to have at least one convective band per winter storm with as many as three or four per storm being fairly common. One band is usually associated with cold fronts as they pass through the county. Frequently these frontal bands are the strongest, longest lasting bands during the passage of a storm. Other bands may occur in either pre-frontal or post-frontal situations. The duration of these bands over a fixed location on the ground can vary from less than one hour to several hours duration. Figure 2 provides a PPI display of a convective band from the Vandenberg AFB NEXRAD radar.

The ground based flare burns were conducted on a random, 50/50, seed or no-seed decision basis. A large network of recording precipitation gauges was installed for the research program. The amount of precipitation that fell from each seeded or non-seeded convective bands was determined at each precipitation gauge location. Average convective band precipitation for seeded and non-seeded events was calculated for each rain gauge location. Figure 3 shows the results of seeding from the ground as contours of the ratios of average seeded band precipitation versus the non-seeded band precipitation. Ratios greater than 1.0 are common in Figure 3 although the area in Kern County is not as meaningful since it is in a rain shadow area. A ratio of 1.50 would suggest a 50% increase in precipitation from seeded convective bands compared to non-seeded bands. These results were statistically significant at a number of the precipitation gauge sites. 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 (Thompson, et al., 1975). If it is assumed that all convective bands could be seeded in a given winter season and that a 50% increase was produced, the result would be a 25% increase in winter season precipitation. Interestingly this 25% number is similar to results from an historical target/control analysis of the potential long-term (1981-2012) effects of the operational seeding program for the Upper Santa Ynez target area in southeastern Santa Barbara County (Griffith, et al., 2015) which indicated increases of 19-21%.

In a similar experiment, Santa Barbara II, Phase II (1970 – 1974), an aircraft was used to release silver iodide freezing nuclei (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 on a 50/50 basis. Figure 4 provides the results of this experiment. Again, a large area of higher precipitation is indicated in seeded convective bands compared to non-seeded convective bands. Notice the westward shift of the effect in this experiment versus the ground-based experiment. This feature is physically plausible since the aircraft seeding was normally conducted off the coastline in the vicinity of Vandenberg AFB (i.e., west of the ground-based release point).
Fig. 3. Seeded/not-seeded ratios of band precipitation for Phase I ground operations, 1967-71 seasons; 56 seeded and 51 not-seeded bands. Areas with ratios of 1.5 or greater are shaded.

Fig. 4. Seeded/not-seeded ratios of band precipitation for Phase II aerial operations, 1970-74 seasons; 18 seeded and 27 not-seeded bands. Areas with ratios of 1.5 or greater are shaded.
3.0 REVIEW AND ANALYSIS OF THE CLIMATOLOGY OF THE PROPOSED TARGET AREAS

Southern and central coastal portions of California have a Mediterranean type of climate, with warm dry summers and wet winters in most areas. The Salinas and Lopez Lake Reservoir drainages lie in the inland portion of San Luis Obispo County, with a semi-arid climate over much of the area and with higher winter precipitation in some coastal mountain locations (an orographic effect). Precipitation data were available for a number of stations in this area. Analysis of the monthly precipitation climatology was conducted using 32 stations in central and western San Luis Obispo County with long-term records that date back, in several cases, to at least the 1950s. The seasonal distribution at these sites should be similar to the Salinas and Lopez Lake Reservoir drainages where only sparse data were available. The multi-station average in Figure 5 shows a distinct peak in January and much lower values during the summer months of June through September.

The proposed target area climatology in terms of “seedable” events is believed to be quite similar to the Santa Barbara County seeding target areas for which seeding results were originally examined in terms of the meteorological conditions and frequency of convective band passages. An analysis of convective band passages over a five-year period in San Luis Obispo County was conducted in order to classify the temperature and wind characteristics associated with these bands. Figure 6 is a wind direction frequency plot for these events at the 700 mb level. This level is important since it is readily obtained from standard upper-air analysis products, it is often representative of the movement of cloud features of interest and it is often near the height of the -5 °C level which is the threshold activation temperature of silver iodide which is the seeding agent proposed for use on this program.

A breakdown of the convective band 700 mb data estimates show that the 700 mb temperature averaged about -4.8 °C during the early portion of a frontal convective band passage and around -6.4 °C in the latter portion of the band passages, resulting in an overall average of a little colder than -5.5 °C. This implies a typical -5 °C level between 9,000 and 10,000 feet MSL. On the cold end of the spectrum, 700 mb temperatures in the -10 °C to -12 °C range will typically bring the -5 °C level down to near 6,000 feet MSL during a significant precipitation period. On the warmer end, 700 mb temperatures around 0 °C are typically associated with a -5 °C level around 12,000 to 13,000 feet MSL, and occasionally higher if there is some mid-level thermodynamic stability involved as with some cases of tropical/subtropical moisture plumes. The height of the -5 °C level is important since silver iodide nuclei begin to activate near this temperature. This means that silver iodide seeding material released from ground sites must rise to this

![Fig. 5. Monthly Precipitation Climatology for San Luis Obispo County, Percent of Annual Total, Multi-Station Average.](image)

![Fig. 6. 700 mb Wind Direction Frequency Plot during Convective Band Passages.](image)
level in order to begin the artificial augmentation of the precipitation processes.

4.0 DEVELOPMENT OF A PROGRAM DESIGN

As previously mentioned, the ASCE 2016 “Guidelines for Cloud Seeding to Augment Precipitation” that “One possible source of estimates of potential program effects on precipitation is the design of operational cloud seeding programs should be based upon prior research programs that provided positive indications of increases in precipitation is previous research and operational programs conducted in similar climatological settings using the same seeding techniques and seeding agents for the new program”. The proposed program for the Lopez Lake and Salinas Reservoir (LLSR) has a unique advantage in this regard since a well-funded winter research program Santa Barbara II, Phases I and II was conducted during the winters of 1967-1973. Furthermore, there have been operational seeding programs conducted most winter seasons since 1981 targeting the Upper Santa Ynez drainages in southeastern Santa Barbara the Twitchell drainage in northern Santa Barbara and southern San Luis Obispo Counties. The latter target area is adjacent to the proposed LLSR target areas. The design of the operational programs since the early 2000’s was based upon the design used in the conduct of the Santa Barbara II research program. A recent peer reviewed evaluation of this operational program, which targets convective bands, provided estimated average results from seeding ranging from 9 to 21% (Griffith, et al., 2015).

The recommended operational five-month period would be November 15th through April 15th each winter season. From a climatology analysis conducted for the county, the vast majority of the annual precipitation in this area occurs during this five-month period. A base or core program is recommended that would involve the siting, installation and operation of three or four ground-based remotely operated flare tree units. These units are known as Automated High Output Ground Seeding Systems (AHOGS). Figure 7 provides a photo of a site being used on the current Santa Barbara winter cloud seeding program. The AHOGS sites are self-contained and powered by solar panels. The project meteorologist can use a computer program to communicate with each site and schedule flares to be fired. Flares weighing 150 grams, containing 16 grams of silver iodide, would be used at these sites. Eight potential sites were identified, located at higher elevations, west to southwest of the target areas based upon the 700 mb wind direction distribution during convective band passages provided in Figure 6. Higher elevation sites are desirable since the silver iodide nuclei would have less distance to travel to reach the -5 °C level than sites that might be sited near sea level.

A cloud seeding aircraft could be added to augment (perhaps for a three or four-month period) the recommended base program using ground-based flare units. Nearly 75% of the annual precipitation for San Luis Obispo County occurs during the December 1 to March 31 period which favors this period for

Fig. 7. Photo of the Harris Grade AHOGS Site.
the addition of a seeding aircraft. Figure 8 provides a photo of a Cheyenne II cloud seeding aircraft used in Santa Barbara County during the 2015-2016 winter season. This seeding aircraft would use the same silver iodide flares as used in the ground-based sites. The pilot would initially fly along the leading edge of the convective bands at the 0 °C to -5 °C level as they approach the San Luis Obispo coastline. The pilot would ignite flares along the fight path moving inland with the band as it progresses over the western part of the county upwind of the two target areas. The location of the convective bands can be observed via on-board weather radar and/or from the NWS Vandenberg AFB NEXRAD radar whose displays may be viewed in the cockpit.

There is a wealth of weather information available via the Internet. There are a number of products that could be useful in the conduct of cloud seeding operations. Specialized computer models can be used in the conduct of this program. These models are of two basic types: 1) those that forecast a variety of weather parameters useful in the conduct of the cloud seeding program (e.g., NAM or WRF) and 2) those that predict the transport and diffusion of seeding materials (e.g., HYSPLIT). An example of a HYSPLIT simulation for a storm period that affected the proposed target areas using eight possible ground-based flare sites is provided in Figure 9. A detailed Operations Plan would be developed for use during each operational season. Specific seeding suspension criteria would be included in this plan.

5.0 ESTIMATED INCREASES IN PRECIPITATION AND STREAMFLOW

Long-term precipitation gauge station records (November-April) were correlated, through the development of regression equations, with either observed or estimated annual (July-June) inflow to the two target reservoirs. Good correlations (as measured by correlation coefficients) were obtained. NAWC then calculated the average inflow values for the two reservoirs. The results obtained from the NAWC evaluation of the Santa Barbara Water Agency program (Griffith, et al., 2015). Estimated 9% or 17% increases were applied to the regression equations to estimate the resulting increases in inflow, based upon the estimated increases in precipitation in an average water year. Table 1 summarizes the estimated average increase in annual inflow.

NAWC did not attempt to estimate what the difference in precipitation increases might be through only using ground-based seeding, only airborne or a combination of the two seeding modes. When considering a ground-based seeding program, the estimated increases in precipitation...
and inflow would likely be lower. Both ground and airborne seeding modes have typically been used on the Santa Barbara program often in the same seeded seasons although ground-based seeding has typically been conducted for five-month periods where airborne seeding, due to its expense, has been conducted for three-month periods. Perhaps a crude approximation could be made by assuming ~9% precipitation increases could be obtained using only ground-based equipment and ~17% increases could be obtained by using a combination of ground-based and airborne seeding.

6.0 ESTIMATED PROGRAM COSTS AND BENEFIT/COST ESTIMATES

Cost estimates were developed to conduct the following: 1) a ground based program 2) an aerial program and 3) a combination program using both seeding modes. Table 2 provides estimated costs per acre-foot and estimated benefit/cost ratios based upon data from Table 1 and the estimated costs. Regarding Table 2, recall the earlier comments about the four AHOGS dispensers, operating for a five-month period, potentially creating the estimated 9% increases. The estimated 17% increases would potentially require 5 months seeding with four AHOGS dispensers and 3 months seeding with aircraft. Effects from aircraft only seeding for five months would possibly fall between the 9% and 17% values.

### Table 1. Estimated Streamflow Increases for 9% and 17% Seasonal November-April Precipitation Increases.

<table>
<thead>
<tr>
<th>Stream Gauge Site</th>
<th>Regression for Lopez Dam Inflow</th>
<th>Regression for Lopez Creek Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>9% precipitation increase</td>
<td>17.8%</td>
<td>13.4%</td>
</tr>
<tr>
<td>Inflow to Salinas Dam</td>
<td>3100 acre-feet</td>
<td>2334 acre-feet</td>
</tr>
<tr>
<td>Inflow to Lopez Dam</td>
<td>2926 acre-feet</td>
<td>2203 acre-feet</td>
</tr>
<tr>
<td>Total increase for 9% precipitation</td>
<td>6026 acre-feet</td>
<td>4537 acre-feet</td>
</tr>
</tbody>
</table>

| 17% Precipitation increase         | 33.7%                           | 26.3%                           |
| Inflow to Salinas Dam              | 5855 acre-feet                  | 4579 acre-feet                  |
| Inflow to Lopez Dam                | 5527 acre-feet                  | 4322 acre-feet                  |
| Total increase for 17% precipitation| 11,382 acre-feet                | 8901 acre-feet                  |

7.0 SUMMARY

Recommendations from the American Society of Civil Engineers (ASCE 2016) publication entitled “Guidelines for Cloud Seeding to Augment Precipitation” include the following:

1. “When possible, the feasibility study for a program should draw significantly from previous research and well-conducted operational programs that are similar in nature to the proposed program (e.g., similar topography, similar precipitation occurrences, etc.).”

2. “The primary purpose of the feasibility study is to answer two questions. First, does it appear that a cloud seeding program could be implemented in the intended target area that would be successful in achieving the stated objectives of the program? Second, are the estimated increases in precipitation expected to produce a positive benefit-cost ratio?”

It was concluded that the technical feasibility is strongly positive for the proposed Lopez Lake and Salinas Reservoir program. The Santa Barbara II Research program was conducted in two phases (ground-based and airborne based seeding modes).
from 1967-1974. This program demonstrated that significant increases in precipitation could be achieved when convective bands (common features embedded in coastal California winter storms) were seeded with silver iodide. The Santa Barbara County Water Agency has supported operational seeding programs beginning in 1986 and continuing for most winter seasons to the present (Griffith, et al., 2005). Both ground-based and airborne seeding modes have typically been utilized. A recent evaluation of this operational program indicated average December-March precipitation increases ranging from 9% to 21% (Griffith, et al., 2015). NAWC’s response to the second ASCE recommendation, economic feasibility, is also strongly positive. ASCE 2016 suggests a 5/1 or greater benefit/cost ratio for a program to be considered economically feasible. The ratios in Table 2 are considerably greater than this 5/1 ratio. Therefore, the proposed program is considered to be a feasible means of augmenting the storage in the two proposed target reservoirs.

8.0 REFERENCES

ASCE, 2016: Guidelines for Cloud Seeding to Augment Precipitation. ASCE Manuals and Reports on Engineering Practice No.81, American Society of Civil Engineers, Reston, Virginia.


