

**A LEVEL II WEATHER MODIFICATION FEASIBILITY STUDY  
FOR WINTER SNOWPACK AUGMENTATION  
IN THE SALT RIVER AND WYOMING RANGES IN WYOMING**

Don A. Griffith, Mark E. Solak and David P. Yorty  
North American Weather Consultants, Inc.  
Sandy, Utah 84093  
and  
Bruce Brinkman  
Wyoming Water Development Commission  
Cheyenne, Wyoming 82002

Abstract. North American Weather Consultants performed a feasibility/preliminary design study for a potential operational winter cloud seeding program for the Salt River/Wyoming Ranges in Wyoming, under contract to the Wyoming Water Development Commission. The Desert Research Institute (DRI) conducted atmospheric modeling as part of this study. The primary project goal is to increase winter snowpack in the target area through operational cloud seeding. An average increase of 10% in November through March precipitation via cloud seeding was calculated, using results from the Climax I and II research programs. Simulations using empirically derived snowpack-streamflow relations yielded increases in streamflow from three seeding modes totaling approximately 109,500 acre feet ( $1.35 \times 10^8 \text{ m}^3$ ) on average. The costs per acre foot for the estimated increases in streamflow range from \$1.91 to \$7.13 per acre foot of additional water and associated benefit/cost ratios range from 5.8/1 to 1.6/1, depending on the seeding mode(s). A preliminary design for an operational winter cloud seeding program is described. One preliminary winter season of supercooled liquid water and lower-level temperature and wind observations is recommended, to determine the frequency of low-level temperature inversions during seedable periods. The DRI case study modeling results indicated that such inversions could inhibit the effectiveness of low elevation ground based seeding releases.

## 1. INTRODUCTION

The Wyoming Water Development Commission (WWDC) contracted with North American Weather Consultants (NAWC) of Sandy, Utah for performance of a comprehensive study of the feasibility/design of applying modern cloud seeding methodology for winter snowpack augmentation in the Salt River and Wyoming Ranges (SRWR) (Griffith, et al, 2006). This executive summary presents the key elements, findings, conclusions and recommendations of the feasibility/design study. The study includes a survey of relevant prior research and operational seeding programs, considerable analysis of project area-specific historical weather data, computer modeling and assessment of potential cloud seeding methods, plus evaluation techniques. Procedures and recommendations of the ASCE publication entitled "Standard Practice for the Design and Operation of Precipitation Enhancement Projects" were utilized where appropriate

(ASCE, 2004). A preliminary operational project design is presented, including identification of permit and reporting requirements. The study also includes hydrologic estimates of the potential project yield in terms of additional runoff and the estimated costs associated with conduct of the project, based on different seeding modes. Preliminary benefit/cost estimates for the proposed project design are presented.

The specific task areas comprising the full feasibility/design study include:

- Scoping Meetings/Project Meetings/Outreach
- Review and Summary of Previous Data
- Climatology of the Project Area
- Development of Preliminary Project Design
- Establishment of Operational Criteria

- Environmental Consequences/Legal Implications
- Permitting/Reporting
- Access/Easements
- Evaluation Methodology
- Potential Benefits/Hydrologic Assessment
- Cost Estimates
- Preliminary Benefit/Cost Analyses
- Reports and Executive Summaries
- Climatological Monitoring of Study Area

## 2. PROJECT GOALS AND SCOPE

**The primary project goal is to increase winter snowpack in the target area through implementation of an operational cloud seeding project, at a favorable benefit/cost ratio without producing any significant negative environmental impacts, and its scope reflects that primary goal.** Seeding operations are to be conducted on a non-randomized basis. Randomization is a technique often used in the conduct of research programs whereby approximately one-half of the potential seed cases are left unseeded to allow a comparison with the seeded cases (Hess, 1974). Evaluation efforts are to be developed and incorporated. Limited investigational elements are included in the design, whereby measurements highly focused on a) identifying the presence of supercooled liquid water, the substance targeted by glaciogenic (ice forming) seeding methods and b) characterizing the vertical atmospheric structure via project specific rawinsonde (balloon) soundings are recommended for conduct on a phased rather than ongoing basis, to help maintain program cost effectiveness. Beyond a recommended "core program", "piggybacked" research components could be added on a non-interference basis if interest develops and adequate additional funding from other sources is obtained.

## 3. PROJECT AREA

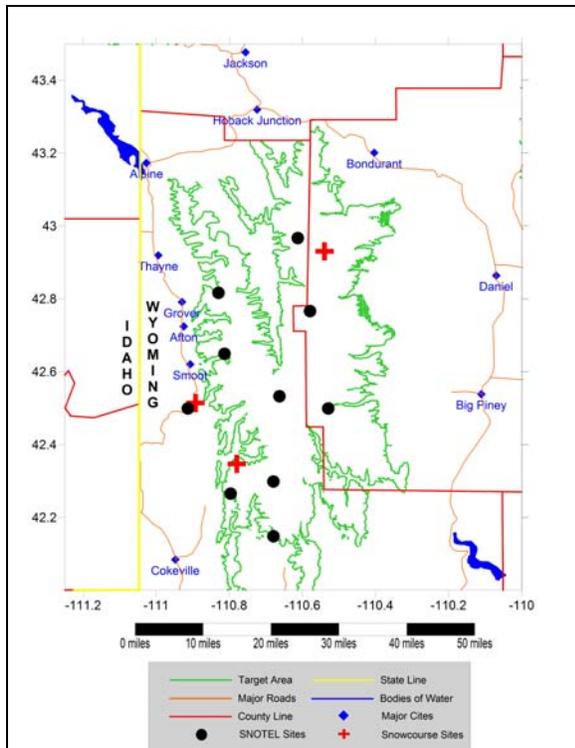
The proposed project target area consists of the terrain above 8,000 feet MSL (2440 m) elevation in the parallel, north-south oriented Salt River and Wyoming Ranges in western Wyoming near the border with Idaho, comprising an area of about 3,590 square miles (9,298 km<sup>2</sup>). The target area is shown in Figure

1. The Greys and Salt Rivers originate in the target area, draining north to join the Snake River at Palisades Reservoir. Several streams drain from the eastern slopes of the Wyoming Range, contributing to the Green River and Fontenelle Reservoir. Both Palisades and Fontenelle have hydroelectric power generation facilities, as do the Hams and Smith Forks, which flow from the southern portion of the target. Runoff from the target area is also of benefit to agriculture and municipalities, as well as recreational interests. Approximately 75% of the annual precipitation in the target area accumulates during the October-April period, with area average snowpack water equivalent on April 1 of about 22 inches (56 cm).

## 4. SEEDING PROJECT PRELIMINARY DESIGN

### 4.1 Seeding Methods and Materials

Prevailing temperature regimes favor use of silver iodide, the most commonly used glaciogenic seeding agent, as the most effective seeding material. Regional National Weather Service (NWS) atmospheric soundings thought to reasonably represent periods of storminess observed in the proposed target areas over a four-winter period (2001-02 through 2004-05) were analyzed to document the vertical structure of the winter storm environment. Analysis of the more than 150 soundings suggests that effective seeding can frequently be accomplished using lower elevation, ground-based silver iodide nuclei generators. Seedable storm periods were defined as storm periods when estimated cloud top temperatures were  $\geq -26^{\circ}\text{C}$ , based upon results from the Climax I and II research experiments (see section 5.0) The data also show that in about two-thirds (67%) of the seedable storm periods manually operated generators at lower elevations (the lowest cost release method) can be effective. That indication was based upon the following criteria: 1) the cloud top temperature was  $\geq -26^{\circ}\text{C}$ , 2) the low level atmospheric stability (surface to 700mb), determined using the NWS soundings and project area-specific surface temperature data, was neutral or slightly stable and 3) the 700 mb temperature was  $\leq -5^{\circ}\text{C}$ . That seeding method has been used for decades to good effect on a seeding project for the Smiths Fork portion of the SRWR target from the 1950's through the mid-1980's (Griffith, et al, 1983) as well as in other climatologically and



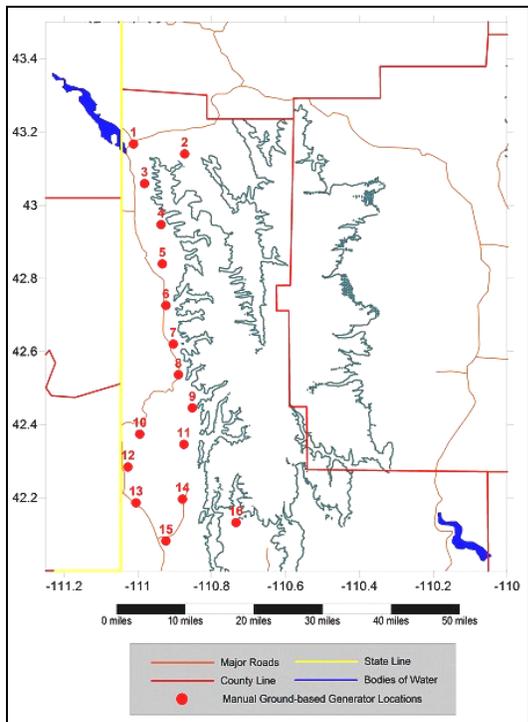
**Figure 1. Potential Target Areas with Snow Monitoring Sites**

topographically similar areas of the west. Recommended locations are in the foothills and near the mouths of canyons. **The recommended “core” operational project design, therefore, incorporates this method as its foundation.** A basic network of about sixteen sites is recommended, with approximate locations shown in Figure 2. Additional generators could be added to the basic network in an attempt to insure overlap of the seeding plumes (Griffith, et al, 1992). Such additions of manual generators would not be particularly costly. The proposed generator locations reflect the prevailing westerly-component flow during winter storms. Given the relatively narrow mountain barriers in the target area, use of a fast-acting silver iodide solution formulation is recommended.

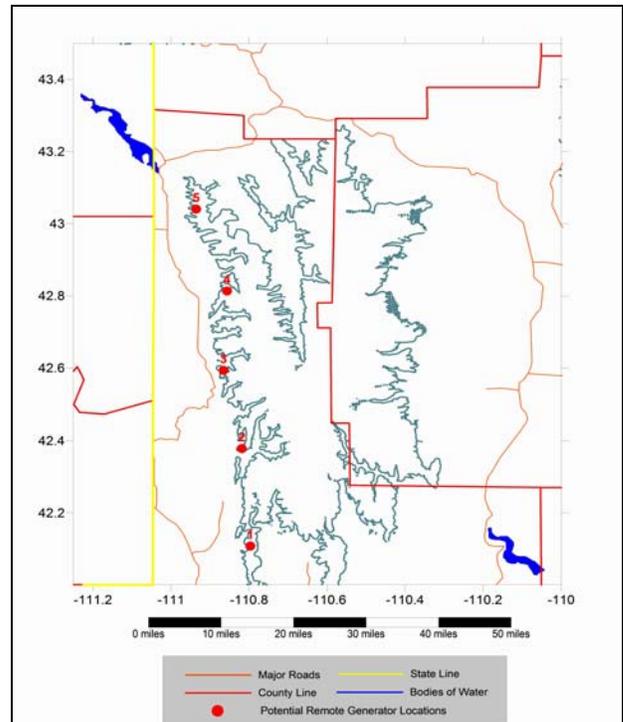
Atmospheric temperature inversions could inhibit the vertical transport of seeding materials from lower elevations to the supercooled liquid water regions over the upwind barrier slopes in some of the storm periods (Super, 1999). This factor was identified and documented in analysis of four seasons of

atmospheric soundings and in computer modeling studies for the area. Further, some areas where ground-based seeding would be desirable are not readily accessible during the winter months. For these reasons, it is recommended that an array of approximately five remotely controlled ground-based generators be considered for installation along the upwind (western) side of the Salt River Range at mid-barrier elevations. Their approximate locations are shown in Figure 3. Given the relatively narrow mountain barriers in the target area, use of a fast-acting silver iodide solution formulation is recommended for use in these systems as well. The recommendation of remotely controlled systems is predicated on a favorable benefit/cost ratio being associated with their inclusion, if suitable locations can be found on state or private lands or, if on federal lands, with the assumption that special use permits, as required, can be obtained for the desired locations. It is recognized that additional costs associated with environmental documentation would be involved in obtaining these special use permits. The four season rawinsonde analysis indicates that use of remotely controlled ground-based generators would enable seeding of an additional 17% of the total number of seedable storm periods, beyond the 67% considered to be effectively seedable using manually operated, lower elevation generators. The criteria used in this determination were: 1) the cloud top temperature was  $\geq -26^{\circ}\text{C}$ , 2) the low level atmospheric stability was moderate to very stable, 3) the 700 mb temperature was  $\leq -5^{\circ}\text{C}$ .

Airborne seeding with silver iodide may be conducted when the temperatures near the mountain crest height are too warm for silver iodide released from ground-based sites to be effective. Assuming the ability to fly safely in the desired areas upwind of the intended target area, aircraft can be flown at a temperature level appropriate for activation of the temperature dependent silver iodide nucleation process. The four season rawinsonde analysis indicates that use of aircraft seeding would enable seeding of an additional 16% of the total number of seedable storm periods, beyond the 84% considered to be effectively seedable using manually operated lower elevation generators and remotely controlled ground-based generators. The criteria used in this determination were: 1) the cloud top temperature was  $\geq -26^{\circ}\text{C}$  and 2) the 700 mb temperature was  $> -5^{\circ}\text{C}$ . The area storm



**Figure 2. Approximate Locations of Manually Operated Ground-Based Generators**



**Figure 3. Approximate Locations of Remotely Controlled, Ground-Based Generators**

climatology indicates that airborne seeding could be of particular benefit during the month of April if operations are extended. This is due to the typically warmer storm conditions and the aircraft's ability to place the seeding material in more elevated supercooled liquid water zones. If airborne seeding is to be conducted, it is recommended that turbine engine aircraft be used. This recommendation is based primarily on aircraft performance as it relates to safety considerations, given the airframe icing that occurs during seeding operations. Potential bases of operations for aircraft include airports at Pocatello and Idaho Falls in Idaho and Jackson, Wyoming. A decision regarding inclusion of aircraft seeding in the project design can be made at the sponsor's discretion, if a benefit/cost analysis of this option is favorable. It is conceivable that the "core program" utilizing manually operated ground generators could be augmented by aircraft seeding without the use of remotely controlled, ground based silver iodide generators. This combination may result in the ability to seed a large majority of the seedable events.

Potential use of additional seeding methods was considered, including dry ice dispensed from aircraft, venting of liquid propane from mid-high elevation ground sites, and ground-launched rockets. For lack of evidence of significant large area positive effects, logistical issues, and benefit/cost considerations, these seeding methods are not recommended for implementation in the SRWR project.

#### 4.2 Operational Period

The primary seedable period extends from November through March based upon analyses of project-specific precipitation data and NWS rawinsonde data representative of the target area. Although some seeding opportunities can occur outside the period, that five-month period is recommended for active operations because it typically includes the majority of the seedable storms.

#### 4.3 Supplemental Meteorological Measurements

One winter season of supplemental data collection specific to the project area is proposed prior to a decision being made as to whether the fully operational SRWR seeding program should be implemented. Measurements would include rawinsonde (balloon) soundings to better characterize the structure of the storm environment, especially levels below mountain crest height. A strategically located ridge-top icing rate detector site would document the occurrence of supercooled liquid water. Microwave radiometer observations would document the vapor and liquid water in the winter storms. Analysis of data from these systems will help fine-tune the preliminary operational design. Comparison of the ice detector records with the radiometer data will indicate the extent to which a permanent ice detector site would be helpful in real time operational cloud seeding decision-making. This season of data collection would provide information to complete the preliminary project design.

#### 4.4 Seeding Effectiveness Evaluation

Since an operational cloud seeding program is proposed, in response to the prospective sponsors' specification, evaluations of the effectiveness of the cloud seeding program will be based on historical target and control techniques using NRCS SNOTEL target and control sites. Control and target sites were selected from similar elevation ranges to lessen any potential impact of climatic variability. Both precipitation and snow water content regression equations are provided in the report. It is also proposed that some snow chemistry analyses be conducted, verifying that silver above-background levels are observed at various sampling points in the target areas.

#### 4.5 Key Elements of the Recommended Preliminary Seeding Project Design

- The suggested target area includes elevations above 8,000 feet MSL (2440 m) located in Lincoln and Sublette Counties.
- A "core program" is proposed utilizing ground-based, manually operated silver iodide generators. This "core program" could be augmented through the

addition of remotely controlled ground generator and/or aircraft seeding modes.

- Supplemental mid-high elevation remotely controlled silver iodide generators are recommended for consideration, subject to benefit/cost considerations.
- Fast-acting silver iodide seeding solution formulations are recommended.
- Airborne seeding may be considered, subject to benefit/cost considerations.
- Seeding operations should be conducted full-time, with no randomization.
- Seeding suspension criteria will be followed with primary emphasis on percent of normal snowpack values and avalanche concerns.
- The primary seeding season will be November through March, with possible extension into April.
- Radar data from the National Weather Service radars can be used to view storms approaching the project area; project-specific radar is not considered necessary.
- A one-season campaign of rawinsonde, radiometer and ice detector measurements are recommended. Analysis of the one-season specialty measurements, in conjunction with other routinely available meteorological information, will assist in completion of the final project design.
- Surface snow chemistry sampling and analyses should be used to verify seeding material targeting.
- Historical target and control regression methods should be used to estimate seeding effectiveness.

### 5. POTENTIAL YIELD/BENEFITS

Analysis of the variability in storm temperature structure over the project area for a four season period was performed and then applied in conjunction with 500 mb partitioned seeding results from a research program in Colorado (Climax I and II) to estimate the anticipated effects for the SRWR project (Grant, 1986). The validity of the Climax experiment results have been debated in the literature with concerns expressed about "luck of the draw"

favoring the seeded data set. Mielke, et al, 1981 reported on a comprehensive re-analysis using covariates of the Climax I and II data sets. This analysis reported stronger statistical evidence than the original analysis but with a reduction of indicated increases in the stratification of cases with 500 mb temperatures  $\geq -20^{\circ}$  C from 41 to 25%. Hess (1974), indicated a 10% increase from Climax I and II when 500 mb temperatures were  $\geq -26^{\circ}$  C and  $< -20^{\circ}$  C. Due to questions regarding the 500 mb height representing cloud top, our analysis of the four seasons of rawinsonde data utilized actual estimates of cloud top temperatures from NWS soundings. The concept that warmer topped clouds frequently contain supercooled liquid water is confirmed by Super, 1990 where the following summary statement is made; "There is remarkable similarity among research results from the various mountain ranges. In general, supercooled liquid water is available during at least some portions of many storms. It is usually concentrated in shallow clouds with warm tops."

The analysis applied the varying Climax seeding effects within cloud top temperature categories according to their seasonal occurrence in the SRWR cloud top temperature data during a multi-year period. Using that method, the multi-season average estimated increase in April 1<sup>st</sup> snow water content is 10%. That factor was applied at twelve surface measurement sites in the target area, yielding estimated increases in average April 1 snowpack water equivalent ranging from 1.27 in (3.23 cm) to 3.05 in (7.75 cm) and a target area average difference (increase) of 2.17 in (5.45 cm) of water due to seeding. Hydrologic evaluations correlating average April 1<sup>st</sup> snow water content with resultant streamflow for a number of project-specific sub-basins indicated that the estimated 10% increase in April 1<sup>st</sup> snowpack water equivalent (content) in the SRWR would result in an average increase in annual runoff from the proposed seeding target area of about 109,500 acre feet ( $1.35 \times 10^8$  m<sup>3</sup>) of additional runoff. Not all streams originating in the target areas are gaged. As a consequence the 109,500 acre foot number is likely a conservative estimate of potential additional runoff.

Such results compare favorably with a review of the estimated results of several similar winter orographic seeding projects conducted in the western states, some for decades,

supporting the potential for precipitation augmentation ranging from about 5% to 15%. Additionally, these estimates can be supported by the published policy statements of the Weather Modification Association (WMA, 2005) and the American Meteorological Society (AMS, 1998), which state that there is statistical evidence that precipitation from supercooled (clouds whose temperatures are  $< 0^{\circ}$  C) orographic clouds (clouds that develop over mountains) has been seasonally increased by about 5% to 15%. A similar statement published by the World Meteorological Organization also indicates that there is statistical evidence for precipitation increases from supercooled orographic clouds, although not stating a range of effect. The American Society of Civil Engineers supports and encourages development of atmospheric water (also known as weather modification or cloud seeding) for beneficial uses, and has published a standard and manual of professional practice for cloud seeding for the purpose of precipitation enhancement (ASCE, 2004, 2006).

In summary, a reasonable expectation of the average effect of seeding is about a 10% increase in area average snow water equivalent in the SRWR, which amounts to a little over two additional inches of water content in the project area average snowpack as of April 1.

## 6. BENEFIT AND COST CONSIDERATIONS

Estimated increases in runoff for a "core program" using only manually operated silver iodide generators were calculated along with the attendant estimated costs. The estimated additional runoff and attendant costs were then calculated for 1) the addition of a network of remotely controlled silver iodide generators to the "core program", and 2) the addition of a network of remotely controlled silver iodide generators plus one cloud seeding aircraft to the "core program." Preliminary estimates of the potential benefits were also calculated in the study. Estimates of increases in runoff, costs and benefit/cost ratios are summarized in Tables 1, 2 and 3.

The estimated cost per acre foot of additional runoff ranges from \$1.91 to \$7.13 depending upon the method(s) of seeding, with attendant benefit/cost ratios ranging from 5.8 to 1.6. The additional water would benefit regional

water supplies for agricultural, municipal use and hydroelectric power generation. If the value of the additional water volume to recreation, fisheries, tourism, threatened and endangered species, and downstream uses could be quantified and included, the projected value would be even greater.

## 7. CONCLUDING REMARKS

The feasibility/design study summarized in this article has determined that an effective operational winter cloud seeding program can be established and conducted for the Salt River and Wyoming Ranges. The program has the potential to enhance the snowpack by ~10% during an average winter season, with the resultant additional annual runoff estimated to be about 109,500 acre feet ( $1.35 \times 10^8 \text{ m}^3$ ) utilizing the combination of three different seeding methods. Conduct of the proposed single winter season of area-specific meteorological monitoring prior to the start of operational seeding would serve to refine the preliminary project design.

## 8. REFERENCES

- American Meteorology Society, 1998: Policy statement: Planned and inadvertent weather modification. *BAMS*, **79**, 2771-2772.
- ASCE, 2004: Standard Practice for the Design and Operation of Precipitation Enhancement Projects. ASCE/EWRI Standard 42-04, Reston, Virginia, 63 pp.
- ASCE, 2006: Guidelines for Cloud Seeding to Augment Precipitation. ASCE Manuals and Reports on Engineering Practice No. 81, 181 pp.
- Grant, L., 1986: Hypotheses for the Climax wintertime orographic cloud seeding experiments. *Precipitation Enhancement – A Scientific Challenge, Meteor. Monogr.*, No. 43, Amer. Meteor. Soc., 105-108.
- Griffith, D.A., J.R. Thompson and R.W. Shaffer, 1983: Winter orographic cloud seeding northeast of Bear Lake, Utah. *J. Wea. Mod.*, **15**, 23-27.
- Griffith, D. A., G. W. Wilkerson, W. J. Hauze and D. A. Risch, 1992: Observations of Ground Released Sulfur Hexafluoride Tracer Gas Plumes in Two Winter Storms. *J. Wea. Mod.* **24**, 49-65.
- Griffith, D.A., M.E. Solak, D.P. Yorty, A.W. Huggins and D. Koracin, 2006: Level II Weather Modification Feasibility Study for the Salt River and Wyoming Ranges, Wyoming. NAWC report No. WM 06-2 to the Wyoming Water Development Commission, 265 pp.
- Hess, W. N., 1974: *Weather and Climate Modification*. John Wiley & Sons, Inc., New York, New York, 207, 299.
- Mielke, P.W., Jr., G. W. Brier, L.O. Grant, G.J. Mulvey, and P.N. Rosenzweig, 1981: A Statistical Reanalysis of the Replicated Climax I and II Wintertime Orographic Cloud Seeding Experiments. *J. Appl. Meteor.*, **20**, 643-659.
- Super, A. B., 1990: Winter Orographic Cloud Seeding Status in the Intermountain West. *J. Wea. Mod.* **22**, 51-75.
- Super, A. B., 1999: Summary of the NOAA/Utah Atmospheric Modification Program: 1990-1998. *J. Wea. Mod.* **31**, 51-75.
- WMA, 2005: WMA Capabilities Statement on Weather Modification, [www.weathermodification.org](http://www.weathermodification.org).

**Table 1**  
**SRWR Snowmelt Runoff Augmented Amounts and Monetary Values**  
**(average annual runoff in acre feet, using the three seeding modes)**

Value	Greys	Salt	Green	Bear	Total
Avg. Annual (AF)	467,575	165,097	276,442	134,443	1,043,557
Augmented (AF)	49,095	17,335	29,026	14,117	109,573
Ag Value (\$11.00/AF)	\$27,002	\$120,132	\$172,414	\$104,042	\$423,590
Muni. Value (\$87.50/AF)	0	\$106,177	\$152,387	\$98,819	\$357,383
Hydroelectric Value (\$6.56/AF)	\$305,960	\$34,115	\$76,164	\$23,152	\$439,391
Total Value	\$332,962	\$260,424	\$400,965	\$226,013	\$1,220,364

**Table 2**  
**Seeding Program Costs**

	Core Program*	Add Remotes*+	Add Aircraft
Year 1	\$133,775	\$173,800	\$ 443,400
Year 2	\$140,464	\$125,890	\$465,570
Year 3	\$147,487	\$132,185	\$488,849
Year 4	\$154,861	\$138,794	\$513,291
Year 5	\$162,604	\$145,733	\$538,955
Average	\$739,191/5= \$147,838	\$716,402/5= \$143,280	\$2,450,065/5= \$490,013

\* Includes equipment acquisition and installation costs amortized over 5-year period  
+ Does not include additional costs of environmental analyses if sited on federal lands.

**Table 3**  
**Estimated Average Costs to Produce Additional Annual Streamflow**  
**and Estimated Benefit/Cost Ratios**

	Core Program (CP)	CP Plus Remote CNG's	CP Plus Aircraft	CP Plus Remote CNG's and Aircraft
Ave. Cost to Produce Extra Water	\$147,838	\$291,118	\$637,851	\$781,131
Ave. Water Year Streamflow Increase	77,468	90,398	96,643	109,573
Cost Per AF	\$1.91	\$3.22	\$6.60	\$7.13
Benefit	\$862,797	\$1,006,800	\$1,076,361	\$1,220,364
Benefit / Cost	5.8	3.5	1.7	1.6

