Weather Modification–
Medicine Bow/Sierra Madre Ranges Final Design and Permitting Study

Executive Summary prepared for

Wyoming Water Development Commission
State of Wyoming

by

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8 December 2017

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Executive Summary

A Final Design and Permitting Study was performed to establish an operational weather modification program targeting the Medicine Bow and Sierra Madre Ranges in southern Wyoming. This study was led by the National Center for Atmospheric Research (NCAR) in collaboration with Weather Modification International, and Heritage Environmental Consultants. Twenty tasks were identified by the Wyoming Water Development Commission for the study, including:

1. scoping and project meetings;
2. reviewing previous studies and data;
3. climatological analysis of the project area;
4. development of a preliminary project design;
5. model evaluation for the preliminary project design;
6. field surveys of potential ground-generator locations;
7. assessing the access/easements and permitting/reporting for potential generator sites;
8. operational criteria development;
9. reviewing environmental and legal considerations;
10. providing program evaluation methodologies;
11. potential benefits analysis;
12. cost estimates;
13. development of a cost/benefit analysis of the potential program;
14. finalization of the project design;
15. environmental analysis and permitting;
16. discretionary tasks;
17. preparation of the final report deliverable;
18. giving presentations on the final results;
19. climatological monitoring of the study area; and
20. a model evaluation of the Wyoming Weather Modification Pilot Program (WWMPP) Randomized Statistical Experiment (RSE).

Two public scoping meetings were held at the beginning of the project in locations near the Medicine Bow and Sierra Madre Ranges. The first was in Saratoga, Wyoming on 21 September 2015, and the second in Savery, Wyoming on 24 September 2015. The meetings provided the public with an overview of the scientific concept of cloud seeding, a summary of the previous studies in Wyoming, and a description of the plans for the current study.

A review of previous data found that numerous research investigations have improved the understanding of how to use silver iodide (AgI) seeding to enhance snowfall in winter orographic clouds. These include the recently concluded Wyoming Range Phase II Feasibility Study, and the draft WWMPP, which encompasses the same mountain ranges as those investigated in this study. The results from these studies were reviewed in the preparation of this report to ensure consistency with the most recent recommendations for cloud-seeding program design.

Noteworthy results from the draft WWMPP report asserted that while the RSE was statistically inconclusive, an "accumulation of evidence" analysis approach suggested seasonal precipitation increases of 5–15% in seedable storms over a winter season. It also demonstrated the capability of numerical models to realistically simulate snowfall distributions, as well as simulate seeding effects via a seeding parameterization.

The review of previous data summarized the various options for cloud seeding (e.g., seeding agents, method of delivery, etc.). Liquid-propane seeding was determined to be an ineffective seeding option for the study area because seeding impacts are spatially limited due to the requirement that the liquid propane must be released within supercooled clouds. In addition, manual ground-based AgI generators were experienced as challenging to deploy and operate in the project area, given the limited options for accessible and effective generator placement. For manual generators to be activated and deactivated during the winter months, locations would need to be sited at lower elevations around the Medicine Bow and Sierra Madre Ranges, potentially creating a situation where the AgI plume could be blocked and unable to disperse over the mountains.

A climatological analysis of the Medicine Bow and Sierra Madre Ranges was performed as part of the WWMPP by Ritzman et al. (2015). However, the criteria for seeding used during the WWMPP were established for a *research*-based cloud-seeding program. For the purpose of this study, a climatology analysis was conducted based upon seeding criteria more appropriate for an *operational* cloud-seeding program. Due to a lack of available observations (e.g., soundings and supercooled liquid-water measurements) this study utilized snow-gauge observations and an 8-year, high-resolution (4 km) Weather Research and Forecasting (WRF) model simulation run over the continental United States (CONUS) (WRF-CONUS; Liu et al. 2016) to assess the climatology of seedable conditions in the region. The results of the climatology analysis indicated that the predominant 700-hPa wind direction is westerly. Similarly, the most frequent occurrence of seedable conditions for both ground and airborne-seeding modes were located over the western regions of both mountain ranges. The analysis also indicated that seeding opportunities occurred frequently enough to warrant the placement of a few ground-based generators in southern portions of the Sierra Madre Range. The eastern regions of both ranges were found to be ineffective for ground-based seeding. Airborne seeding was shown to be feasible in all regions, and seeding opportunities were frequent enough to warrant implementation of an airborne program. The fraction of November–April precipitation that fell under seedable conditions was approximately 38% for ground-based seeding, and approximately 56% for airborne seeding. These estimates are based upon the climatological analysis results for the western regions and were used to calculate the estimated streamflow benefits.

Preliminary Project Design, Model Evaluation, and Field Surveys

To test a wide variety of program design options based upon results of the climatological analysis, several groups of potential ground-based generator sites were established. Initially, seven groups of generators were tested (Groups A–D; see Figure 1). Following initial cloud-seeding model simulations, additional generators were added to Group C along the crestline of the Sierra Madre (already pictured in Figure 1), and two additional groups of generator sites were created (Groups E–F; Figure 1) to investigate potential seeding impacts from generators located farther upwind. The preliminary project design focused on ground-based seeding and/or airborne seeding with an operational season of mid-November through mid-April (e.g., 15 November–15 April), utilizing AgI, or more specifically, a silver iodide-salt compound as the seeding agent.

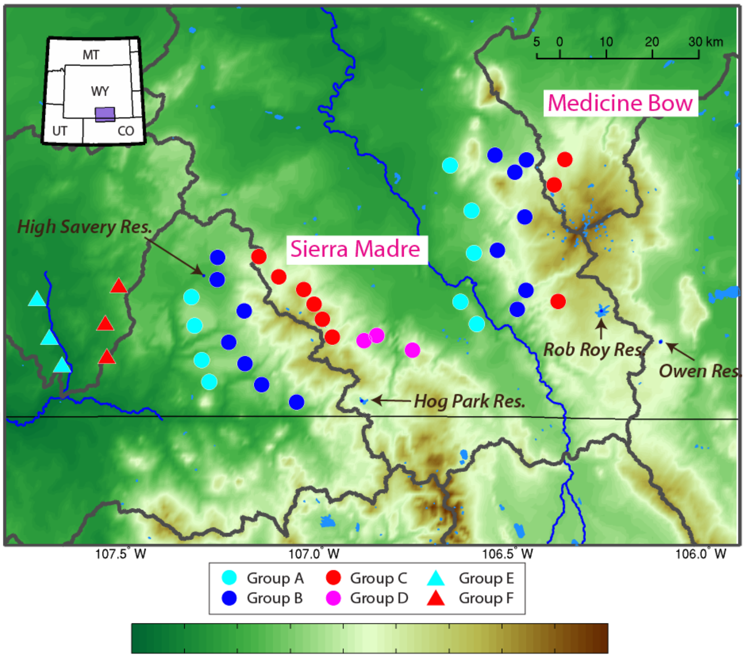

Figure 1. Topography map of the Medicine Bow and Sierra Madre Ranges (m) illustrating the locations of nine ground-based generator design groups.

Four cases were selected from the WWMPP RSE research program to represent a variety of typical seeding conditions in the Sierra Madre and Medicine Bow Ranges. To investigate the potential designs of a ground-based seeding program, these cases were assessed using the NCAR cloud-seeding model parameterization implemented in the Thompson microphysics scheme within the WRF model.

WRF "control" simulations of these four cases showed that supercooled liquid water was present in both ranges throughout the simulations in all cases, which is a necessary condition for seeding operations to commence. The WRF ground-based seeding simulations in these cases showed that: (1) seeding depleted supercooled liquid water in a shallow layer close to the terrain and increased precipitation over the mountain; (2) flow over the Medicine Bow was usually blocked, or forced around the range due to the steeper slope of the topography, although flow from some of the lower elevation generators placed upwind of the Sierra Madre were also occasionally blocked; (3) the simulated seeding effect was not as great if the natural cloud efficiently produced precipitation (as occurred in two of the four cases); (4) seeding simulations using all six of the Sierra Madre generator groups, including the two upwind groups (E–F), produced the greatest combined simulated precipitation increases in *both* ranges for most of the cases tested.

One caveat of note is that the original version of the model seeding parameterization used in this study for the ground-seeding simulations did not include precipitation scavenging of AgI particles, AgI self-coagulation, or AgI dry deposition processes. Therefore, the particles transported from the Sierra Madre to the Medicine Bow and the subsequent simulated seeding impacts in the Medicine Bow were likely overestimated. To address this potential overestimation, two of the initial ground-based seeding cases were re-run using only the Sierra Madre generator groups and the updated seeding parameterization to better understand how additional AgI-removal processes affected the cloud and precipitation, especially downwind in the Medicine Bow Range.

The results of the ground-seeding simulations (Sierra Madre generators only) with the additional AgI-removal processes reduced the AgI concentration and the simulated seeding effect in the Medicine Bow region by about 50% for both of the re-run cases (Figure 2). However, similar or greater simulated seeding effects still resulted in the Medicine Bow when AgI was released from sites only in the Sierra Madre compared with the seeding scenario using only the Medicine Bow generators to target the Medicine Bow. In light of these results, it can be hypothesized that ground-based generators strategically placed only in the Sierra Madre Range could effectively target both the Sierra Madre and Medicine Bow Ranges.

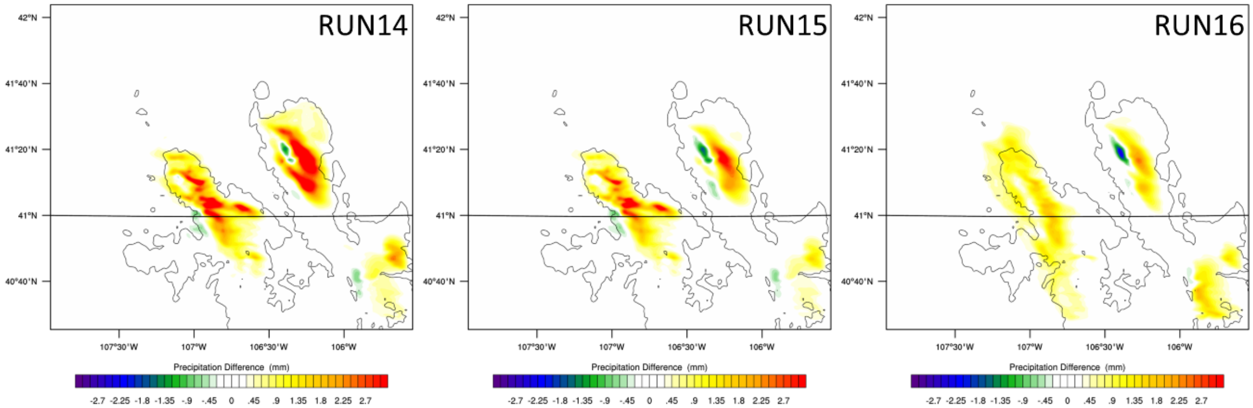

Figure 2. Change in precipitation (mm) due to simulated cloud seeding for model simulations using only Sierra Madre Groups A–F (RUN14 and RUN15) compared with two hours of simulated airborne seeding (RUN16) case in the 13 January 2014 case. RUN14 does not include the newly-added AgI-removal processes, while RUN15 does. The small area of negative changes in precipitation in the Medicine Bow is the result of precipitation changing phase from rain to snow (and snow falling out farther downwind) in the seeding simulation. The assessment area total change in precipitation in these cases is positive.

Two of the four test cases exhibited suitable airborne-seeding conditions, and therefore airborne seeding was simulated for a period of approximately 2 hours in those two cases. Airborne seeding simulations produced increases in total precipitation across the assessment areas similar to that from ground seeding (compare RUN15 and RUN16 in Figure 2 for an example). Airborne seeding simulations, in general, showed impacts over a deeper and broader portion of the atmosphere, and converted the supercooled liquid water to precipitation more efficiently than the ground-seeding scenarios.

During the field surveys, 27 potential ground-based generator sites were visited, and considered for inclusion in the operational project design. Of these 27 sites, 18 were located on federal lands, and 9 on private lands within the Medicine Bow and Sierra Madre Ranges. For each location, land ownership, access descriptions and ratings, and brief descriptions of the sites were presented. As a result of the modeling exercise and field surveys, a total of 35 viable generator sites located on federal, state, and private lands were recommended for possible use, with 23 located on United States Forest Service (USFS) lands.

A Special Use Permit application was submitted to the USFS on 22 February 2016 for an operational cloud-seeding program designed to target the Medicine Bow and Sierra Madre Ranges. The approach for the permit application portion of this study was to provide a maximum number of potential ground-based generators that could be used in the Medicine Bow and Sierra Madre Ranges operational cloud-seeding program, and would be assessed through the federal

NEPA process. The application requested USFS approval to place up to 23 ground-based generators on National Forest administered lands. The Medicine Bow National Forest sent a letter to the Wyoming Water Development Office (WWDO) on 9 August 2016 explaining that the proposed project failed to meet the minimum requirements of the initial screening criteria. The WWDO resubmitted the application on 22 December 2016. The Medicine Bow National Forest responded with a letter to the WWDO on 28 February 2017 initially accepting the amended SUP application and notifying the WWDO that USFS personnel would be in contact to discuss the application approval procedures. The WWDO is currently waiting to be contacted on this matter.

Based on additional model simulations, the total number of viable generator sites was narrowed down from 35 to 23 ground-based generators[†]. Since the model simulations indicated that seeding from sites in the Sierra Madre can produce positive simulated effects on the Medicine Bow under westerly and southwesterly wind flow, one approach to developing a cost-effective operational program would be to place generators only in the Sierra Madre to target both mountain ranges. However, to target the Medicine Bow under northwesterly winds, some sites are still needed in the Medicine Bow on the western and northwestern slopes. The final project design of 23 ground-based generators includes 16 in the Sierra Madre, and 7 in the Medicine Bow (Figure 3). Of the 16 sites in the Sierra Madre, 6 were sited specifically to target the Medicine Bow.

Operational Criteria and Other Program Considerations

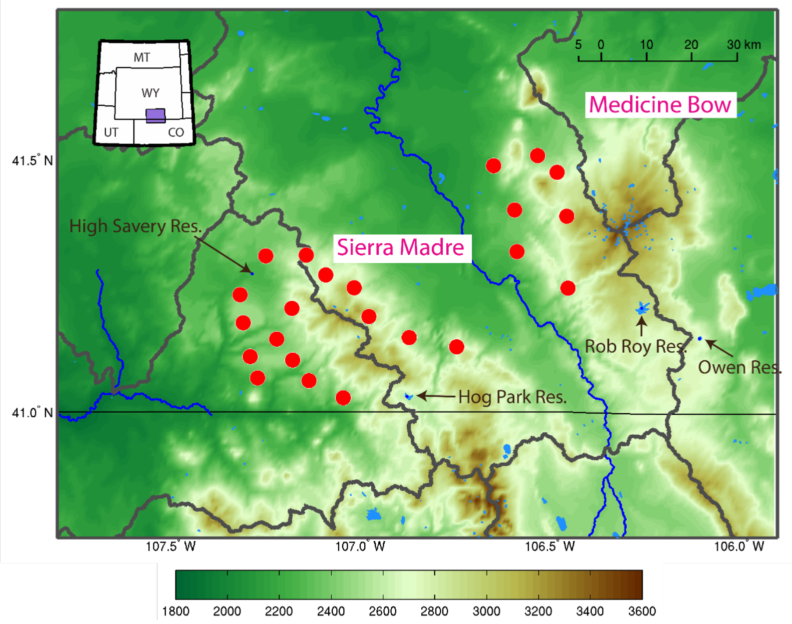

Figure 3. Map of the final recommended design for 23 ground-based generator sites in the Medicine Bow and Sierra Madre Ranges.

Operational seeding criteria were developed for possible ground-based seeding operations as well as for potential seeding with an aircraft. The most critical data required for establishing operational seeding criteria are upper-air temperatures, wind direction and speed, and the existence of supercooled liquid water upwind and over the project target area. Weather observations to determine when most of the operational criteria are met are available in real time via a variety of products available on the internet. However, to obtain all pertinent project specific weather information, the deployment of project soundings and a radiometer is recommended, although not required. A well-designed cloud-seeding program will incorporate seeding suspension criteria to stop or suspend seeding activities that could generate unsafe conditions due to increases in precipitation. Suspension criteria recommended for an

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[†] Note that not all of these are on USFS land, and therefore this set of 23 slightly differs from the 23 included in the USFS permit application.

operational program implemented in the Medicine Bow and Sierra Madre Mountains can be found in Section 9.5.

Other program considerations take into account environmental concerns such as downwind (extra-area) effects, or potential impacts on water and soil quality that surface in relation to the practice of cloud seeding. A large number of studies have been conducted in the western United States related to the potential environmental impacts of winter cloud seeding. In general, these studies found that significant environmental effects due to the possible conduct of cloud-seeding programs in these areas were not expected to occur.

Potential Benefits, Cost Estimates, and Benefit/Cost Analysis Summary

Estimates of streamflow changes due to seeding impacts on precipitation were calculated two ways. One method estimated the change in streamflow relative to a change in precipitation using regressions of historical precipitation and streamflow records, either from gauge measurements and/or long-term model simulation. This method was similar to that used in other weather modification feasibility studies (i.e., Wyoming Range, Bighorn Mountains). In this design study, the 8-year, WRF-CONUS high-resolution model simulation (Liu et al. 2016) was utilized to establish the relationship between changes in streamflow relative to a change in actual precipitation. However, there are several assumptions required for this approach, such as the magnitude of precipitation change due to seeding (i.e., the seeding effect) and the fraction of the assessment area that is impacted by seeding (i.e., the impact area). These assumptions contribute to a substantial range of uncertainty in the final results.

Secondly, streamflow changes from seeding were estimated using a new method that utilizes the WRF-Hydro model, coupled with results of cloud-seeding simulations from the WWMPP. While there are still inherent uncertainties associated with this method, many of the assumptions associated with the previous regression method are removed.

The results of the two methods compared rather well. The regression method found a range of total streamflow increase between ~11,170 and ~49,390 acre-feet (AF), depending on the assumed method of seeding (ground-based versus airborne), the assumed magnitude of the seeding effect (5, 10, or 15% based upon the WWMPP results) and assumed impact area (all assuming a 70% impact area). In contrast, the WRF-Hydro method found a range of 5,000–7,750 AF of streamflow increase (Figure 4). The WRF-Hydro simulation method helped reduce some of the uncertainties in the traditional regression analysis, because it did not need to assume anything about the spatial distribution or magnitude of the seeding effect. Rather, the spatial distribution and magnitude of the seeding effect from the seeding simulations were directly ingested as forcing into the WRF-Hydro simulation. However, at the present time, this simulation represented only two years of simulated seeding cases from the WWMPP; whereas, the regression analysis represented a multi-year average scenario from the climatology analysis. Therefore, averaging the results from the two years of WRF-Hydro simulations yields 6,375 AF of average additional streamflow.

Moreover, the regression analysis results were based upon less stringent conditions for seeding than imposed during the WWMPP (i.e., the climatology analysis used a warmer temperature criterion, no time limit on seeding periods, etc.). The 4-hour time-limit criterion and, in particular, because only one target was seeded at a time, the WWMPP will likely yield reduced seeding effects on streamflow in the WRF-Hydro method than what is estimated using the climatology analysis regression method. The reduction will depend on how long seeding criteria were actually met beyond the 4-hour limit imposed by the WWMPP, but it will likely be reduced by at least half given only one target was seeded at a time in the WWMPP. If the average WRF-Hydro results were doubled, to account for the limited seeding time periods simulated based upon the WWMPP criteria, the results indicate approximately 12,500 AF of additional streamflow could be produced from cloud seeding. This estimate is consistent with the regression analysis result (~11,170 AF) for a ground scenario with just over a 5% seeding effect in seedable storms over a winter season using an assumed 70% impact area.

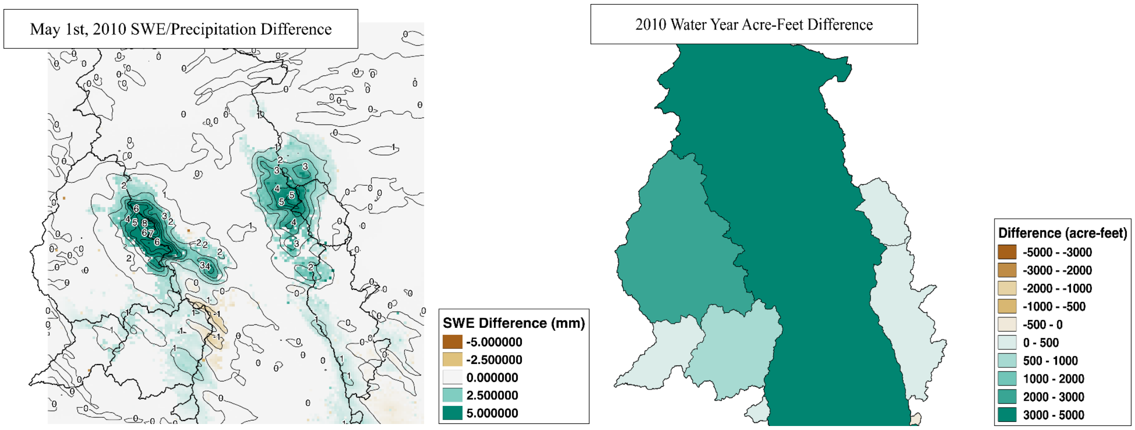

Figure 4. WRF-Hydro simulation results from water year 2010: difference between seeded and unseeded snow water equivalent (SWE) for 1 May 2010 (colored), along with accumulated precipitation difference (mm; contour) on the left, and total accumulated streamflow differences (AF) for the 2010 water year from the non-seeded to seeded simulation by basin on the right. The basins shown in the right panel are outlined in thick black lines on the left for reference.

Cost estimates were prepared for two different operational cloud-seeding program options:

1.) a program with 23 remote-controlled ground-based generators (estimated annual cost: $656,685), and
2.) a single stand-alone aircraft seeding program (estimated annual cost: $361,780).

A preliminary benefit/cost analysis was performed using the estimated range of enhanced average April – July runoff values. American Society of Civil Engineers (ASCE) Guidelines were considered in determining whether the program would be considered feasible. The Guidelines suggest that two questions be answered: is the proposed program technically feasible, and is the proposed program economically feasible? An affirmative answer to both questions is required for the program to be considered feasible. *The evidence presented in this study demonstrates that the program is technically feasible.*

For a program to be considered economically feasible, the ASCE Guidelines recommend that a proposed program have an estimated benefit/cost ratio of 5/1. To determine the benefit/cost ratio, several assumptions need to be considered (e.g., allocation of the water, value of the water, etc.), and were included in the ratio calculations for this study. Of the possible seeding options and levels of seeding effects, airborne seeding met the 5/1 ratio assuming 10% or greater seeding effect and depending on the actual value of water (Figure 5). Ground seeding does not meet the 5/1 ratio, primarily due to the higher program cost when compared with airborne seeding (Figure 5). If the ground-seeding program costs could be reduced (by reducing the number of total generators) while still achieving the desired seeding effect, ground seeding could be more cost effective.

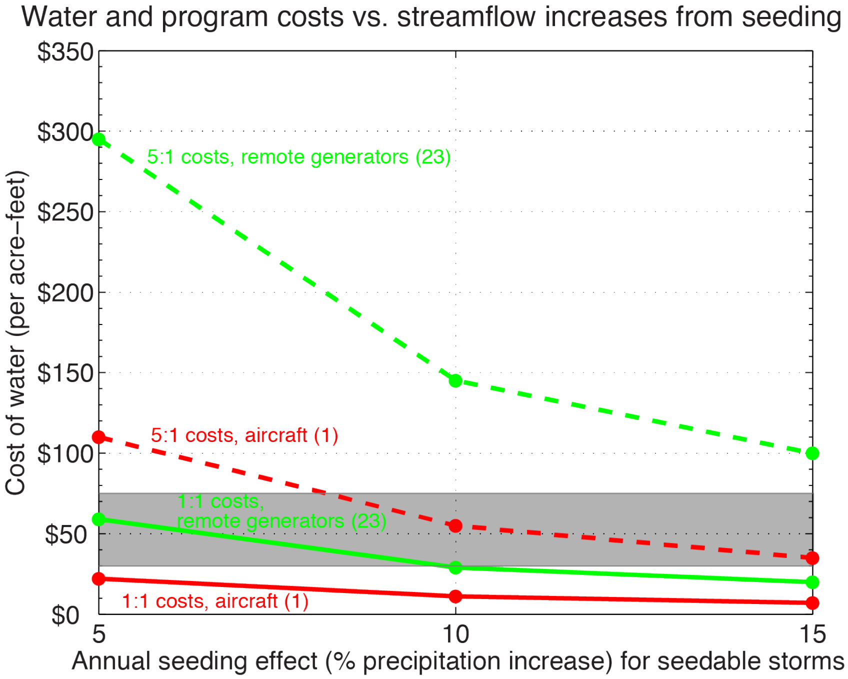

Figure 5. Cost of water for usage and for two estimates of annual seeding program costs (using 70% impact area) for the three levels of estimated streamflow increases resulting from WWMPP annual seeding effects for seedable storms. Gray shading indicates estimated water costs. The solid green and red lines indicate the cost for the 23 remote generator ground-seeding option versus the single aircraft airborne seeding option, respectively, expressed as program costs per acre-foot of streamflow increase (essentially a 1:1 ratio). The dashed green and red lines show the corresponding 5:1 ratios of water costs to program costs.

Model Evaluation of the WWMPP RSE

Instead of collecting additional randomized cases at great expense, an ensemble modeling approach to estimate the impact of ground-based seeding was conducted. This approach is advantageous because conditions with and without seeding can be simulated, allowing the difference of the model simulations to estimate the seeding effect. An ensemble modeling approach also better accounts for initial condition uncertainty, model biases, and random errors in the model simulations. A prerequisite to using a model, however, is that the simulations reasonably represent reality. The WWMPP RSE snow-gauge data and sounding data were compared with the model ensemble and showed reasonable agreement.

This snow-gauge comparison was made with twenty-four model ensemble members for each of three re-analysis forcing datasets with no seeding simulated, with a total of 8,946 simulations to simulate each of the 118 Experimental Units (EUs). The results of the model ensemble approach with and without seeding estimated a mean enhancement of precipitation of 5%, with an inner quartile range of 3 to 7%. These results provide a robust estimate of the impact of ground-based cloud seeding in the Sierra Madre and Medicine Bow Ranges in Wyoming that accounts for key uncertainties in both initial conditions and model physics.

Conclusions and Recommendations

Based on the results of this study, it can be concluded that an operational cloud-seeding program targeting the Medicine Bow and Sierra Madre Ranges is technically feasible. This assertion is supported by the climatological analysis and cloud-seeding model evaluation presented herein, as well as the results previously determined in the same project area during the WWMPP.

Based on the results of this study, an operational cloud-seeding program targeting the Medicine Bow and Sierra Madre Ranges would be economically feasible depending on which type of operational program is implemented (ground or air). The cost effectiveness of a cloud-seeding program is dependent on several factors, including the cost of water and the amount of seeding effect expected. Based on the results of this analysis, airborne seeding is a cost-effective program design option given its lower overall program cost, fewer seeding restrictions due to wind direction or atmospheric stability, and no required permitting fees. However, airborne seeding is limited by aircraft on-station time, which is not reflected in the climatology analysis. For example, a single aircraft may not be able to seed for the entirety of a seedable period if that period is longer than the aircraft can be on station (due to fuel consumption, crew duty limits, etc.). The climatology analysis did not exclude long seedable periods given the aircraft on-station time is currently unknown (dependent on the actual aircraft type selected for the seeding program, the extent of icing conditions encountered in a given flight, etc.). However, accounting for this could lead to a reduction in the amount of precipitation that falls when conditions are seedable by a single aircraft. None of the ground-based seeding scenarios met the 5/1 ratio, and therefore, cannot be considered economically feasible. However conceptually, a ground-based seeding program might be more cost effective if the number of generators in the design were reduced to lower overall program costs, while maintaining seeding effects similar to those presented in this study.

Based on the results of this study, several recommendations specific to the design and conduct of an operational cloud-seeding program in the Medicine Bow and Sierra Madre Ranges are presented:

- Seeding should be conducted using AgI as the seeding agent.
- The seeding season for ground-based and/or airborne operations should be 15 November– 15 April.
- Aircraft seeding is considered technically and economically feasible, whereas ground-based seeding is considered technically feasible only, therefore it is recommended that aircraft seeding be conducted.
- To address whether or not ground-based seeding could be considered economically feasible, an investigation focused on optimizing the operational design in relation to cost and seeding effectiveness should be considered.
- To validate the impacts from seeding with either proposed program design, it is recommended that modeled simulations of additional test cases (ideally an entire season of seeding cases), be considered.
- Basic seeding criteria should be based on readily available (and quickly accessible) meteorological data.
- To accurately assess seeding criteria in the study area specifically, a program would benefit from deploying project-specific instrumentation (i.e., radiometer and soundings),

but these would add additional costs to operate the program that were not considered in the benefit/cost analysis for this study.

- To assess the feasibility of reducing overall program cost, it is recommended that a study to investigate sharing operational resources (i.e., aircraft, staff, weather data, etc.) between seeding programs targeting multiple mountain ranges in the region should be considered.
- To determine the most cost effective approach to sharing operational resources, a cohesive evaluation of all the Wyoming (proposed and operational) weather modification projects, is recommended and should consider multiple project designs (ground-based and airborne).
- The implementation of a statewide, real-time modeling system would provide guidance to determine storm seedability, especially if multiple cloud-seeding programs are implemented within the state. A forecast modeling system will generate a cost savings by identifying when storms have high seeding potential, therefore maximizing cloud-seeding impacts. The model can also serve as a basis for seasonal program evaluation.

Disclaimer

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