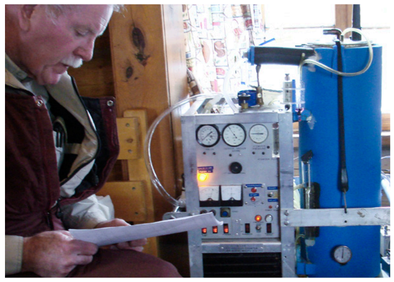
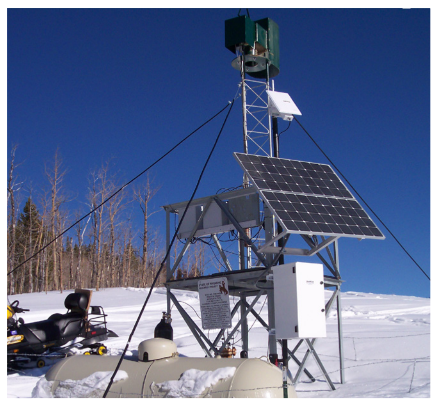
DRAFT EXECUTIVE SUMMARY

The WYOMING Weather Modification Pilot Program • LEVEL II STUDY






PREPARED FOR

Wyoming

WYOMING WATER DEVELOPMENT COMMISSION
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SUBMITTED BY

NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

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UW

HERITAGE ENVIRONMENTAL CONSULTANTS, LLC

DRI Desert Research Institute

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DRAFT EXECUTIVE SUMMARY

The Wyoming Weather Modification Pilot Program (WWMPP) was conducted to assess the feasibility of increasing Wyoming water supplies through winter orographic cloud seeding. Following a Level II feasibility study that found considerable potential for cloud seeding in the state (WMI 2005), the Wyoming Water Development Commission (WWDC) funded the WWMPP (2005-2014) as a research project to determine whether seeding in Wyoming is a viable technology to augment existing water supplies, and if so, by how much, and at what cost. The WWMPP then established orographic cloud-seeding research programs in three Wyoming mountain ranges considered to have significant potential: the Medicine Bow, Sierra Madre, and Wind River Ranges (Figure 1).

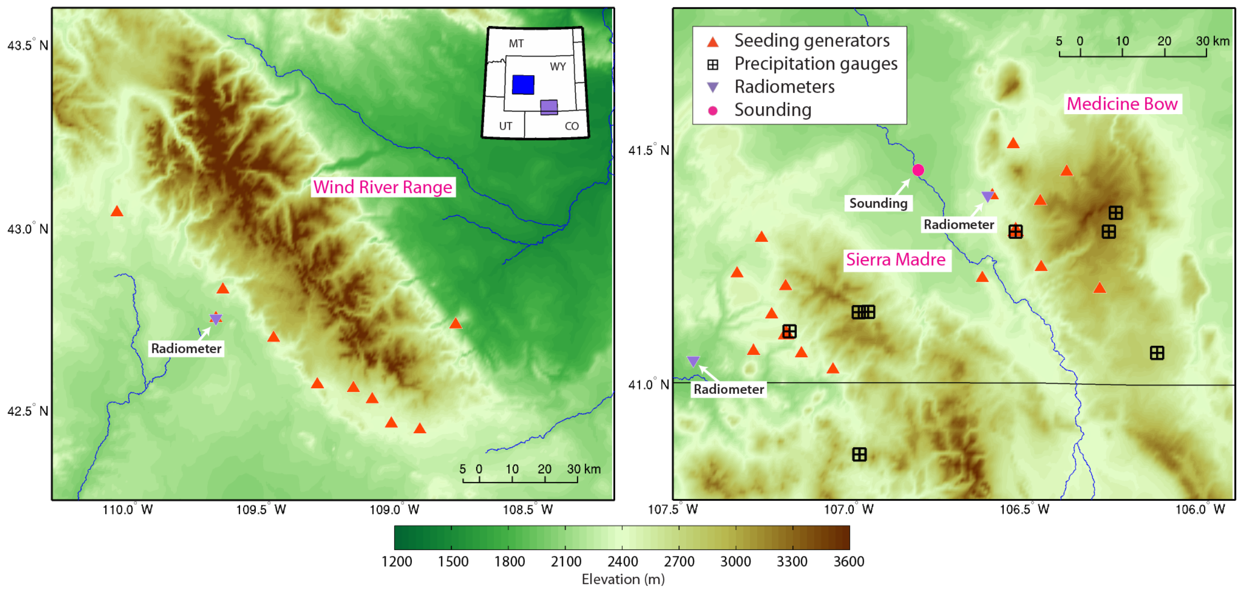

Figure 1. Map of WWMPP facilities (see legend) in the Wind River (left, blue shaded box on inset map) and the Medicine Bow and Sierra Madre Ranges (right; purple shaded box on inset map).

Orographic cloud seeding is a technology designed to enhance precipitation in winter storms with an inefficient precipitation process due to a lack of natural ice nuclei. This inefficiency allows supercooled water to persist for long periods instead of being depleted by ice crystals, which grow and fall as snow. This fact is well documented by the measurement of sustained supercooled liquid water in orographic clouds taken by aircraft and ground-based instruments, such as radiometers. In contrast to natural ice nuclei, artificial ice nuclei, such as silver iodide, will nucleate substantial numbers of ice crystals at subfreezing temperatures of −8 °C (+17 °F) and cooler, creating ice crystals in clouds that are typically too warm for natural ice formation. In the presence of supercooled water droplets, these ice crystals rapidly grow into larger particles that fall to the ground as snow. The technology of orographic cloud seeding uses ground-based generators to produce a silver iodide plume, which is then transported by the ambient wind into orographic clouds to increase precipitation. This process of seeding clouds to create additional snow is complex and to date has not been scientifically verified in well-designed statistical tests.

Two independent contractors were retained by the WWDC to conduct the WWMPP. The seeding operations were performed under a contract with Weather Modification, Inc. (WMI), while the evaluation activities were separately contracted with the Research Applications Laboratory of the National Center for Atmospheric Research (NCAR). Additional contributors to the project included the University of Wyoming (Department of Atmospheric Science, Department of Botany, Department of Civil & Architectural Engineering, and the Office of Water Programs), the Desert Research Institute (DRI), Heritage Environmental Consultants, the University of Alabama, the University of Nevada Las Vegas, and the University of Tennessee. A Technical Advisory Team (TAT) was established early during the project to provide guidance to the Wyoming Water Development Office on the oversight of the program. The TAT facilitated numerous collaborative efforts and data/resource sharing activities during the project. Similarly, local stakeholders were engaged from the program's onset and throughout the life of the project, which was a valuable contribution to the project's overall success.

Design of the WWMPP

The primary goal of the WWMPP was to design and conduct a scientific evaluation of winter orographic cloud seeding. Following guidance from the National Research Council (NRC) 2003 report on weather modification, the evaluation was designed to combine physical, statistical, and numerical modeling studies of environmental, microphysical, and hydrological systems to evaluate the impacts of cloud seeding and determine its economic feasibility. The evaluation was primarily focused on the Medicine Bow and Sierra Madre Ranges where the statistical evaluation was conducted; however, there were additional evaluation components that focused on the Wind River Range.

The main effort in this evaluation was the design, implementation, and completion of a Randomized Statistical Experiment (RSE) to test orographic cloud seeding using a response variable measured by high-resolution snow gauges. In addition to the RSE, the evaluation included physical and modeling studies. These tasks required: permits for siting seeding generators and instruments; numerical modeling studies; physical measurements of silver iodide; verification of silver iodide targeting; establishing the climatological context of seeding opportunities; hydrological modeling of cloud-seeding impacts; monitoring silver in the environment; and studies of extra-area effects. This executive summary is an overview of the final report describing the completion of these tasks.

Based on the conclusions and recommendations of the Level II feasibility study (WMI 2005), and on the resource allocations included in the WWMPP, an iterative design process resulted in a final design (NCAR 2008) that established the RSE, spanning six winter seasons (2008-2014). The design process involved peer reviews, changing and adding facility locations, numerical modeling to verify seeding generator deployment, collecting additional data, and preliminary seeding operations. To meet acceptable scientific rigor for statistical evaluation, the final design required that the analyses and procedures for the RSE be specified *a priori* (prior to beginning operations for the experiment). This design was published in Breed et al. (2014). In addition, a number of physical and numerical modeling studies were conducted to support the RSE evaluation.

The RSE evaluation was based on randomly seeding one or the other of the Medicine Bow and Sierra Madre mountain ranges. Since the two mountain ranges are often affected by the same storms, treating them independently was not statistically appropriate. Therefore, a crossover experiment was designed, in which one range was randomly selected for seeding while the other range served as the "control" (unseeded) comparison. When snowfall in two areas is correlated, treating them in a crossover experiment can decrease the number of cases needed for statistical analysis by a factor of two or more. The criteria for case selection followed the conceptual model of ground-based seeding of winter orographic storms, which required 1) a temperature colder than -8 °C (+17 °F) near mountain top, 2) a wind direction to transport the silver iodide into the targeted clouds, and 3) the presence of supercooled liquid water. The facilities needed for operations and evaluation (see Figure 1) included an atmospheric sounding unit, microwave radiometers, ground-based seeding generators, high-resolution snow gauges located in target areas as well as "control" areas (that would not likely be impacted by cloud seeding), and a high-resolution weather forecast model for forecasting the atmospheric winds, temperatures, stability, and supercooled liquid water prior to calling experimental cases.

The seeding periods ("cases") for the RSE were 4 hours long and the response variable was the 4-hr accumulation of precipitation. The test statistic for the WWMPP design was the root regression ratio (RRR), which is essentially the ratio of seeded to unseeded snowfall with adjustments for the controls (i.e. the estimate of snowfall that would have occurred naturally). Estimates of the number of cases needed for statistical significance using data collected prior to the experiment suggested that changes in precipitation of 15% (and possibly 10%) should be detectable in a five- to six-year program, assuming 65-70 cases per year. This estimate seemed reasonable based on precipitation records and modeling of the 2006-2007 season.

Federal permitting was required to obtain a special use permit to site cloud-seeding generators and snow gauges on Federal lands. This included the National Environmental Policy Act (NEPA) process with the U.S. Forest Service (USFS) involving public comment, and consultation with the U.S. Fish and Wildlife Service under Section 7 of the Endangered Species Act. A Categorical Exclusion was prepared under the NEPA process, resulting in the issuance of the Special Use Permit by the USFS in August 2006. This permit was subsequently renewed in December 2011. Permits from the Wyoming Office of State Lands and Investments were also required to site cloud-seeding generators on State lands. The Wyoming Game and Fish Department was consulted as part of the State permitting process. Permission was granted by several private landowners to place cloud-seeding generators and other instruments used for monitoring and evaluation on their lands. Prior to each season, cloud-seeding permits were also obtained from the Wyoming State Engineer's Office and reports sent to the National Oceanic and Atmospheric Administration Office of Atmospheric Research.

In the six winters during which randomized seeding was performed under the final RSE design, 154 experimental cases were conducted (Figure 2). In the Wind River Range, 131 ground-based seeding events of varying duration were conducted. Seeding-suspension criteria were established for all of the target areas prior to the project to prevent seeding when heavy snowpack or other potentially hazardous conditions developed. Suspension criteria were met three times during the project in the Medicine Bow/Sierra Madre target areas (see Figure 2).

Physical, Statistical, and Modeling Analyses

The evaluation of the project followed the NRC 2003 report guidelines to combine physical, statistical, and numerical modeling studies of cloud seeding. The evaluation results are based on an accumulation of evidence from all three of these areas.

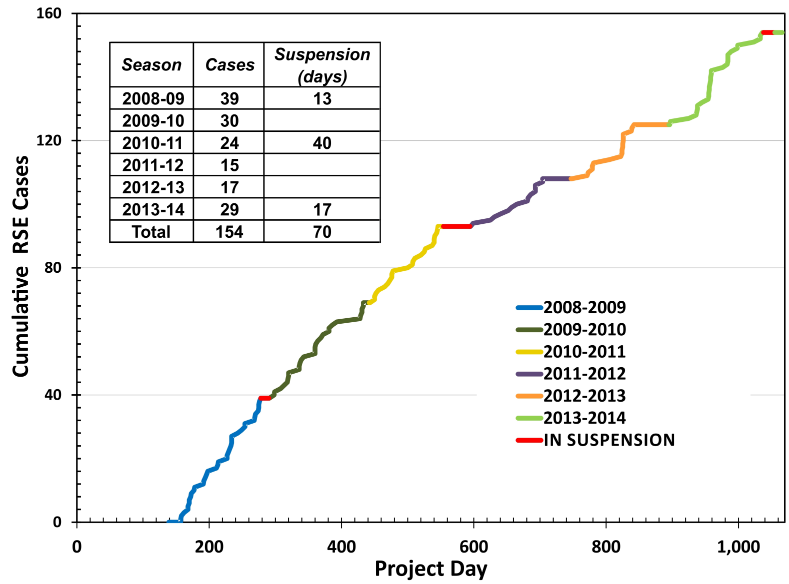

Figure 2. Cumulative number of seeding cases in each of the six seasons of the RSE. Time periods when suspension criteria were met are indicated in red, during which time no new seeding cases were conducted.

Physical Studies

Trace chemical analysis of snow samples from the WWMPP target areas was performed prior to and throughout the WWMPP to determine whether silver from silver iodide cloud seeding was being incorporated into snowfall. Ideally, enhanced snowfall from cloud seeding should be accompanied by enhanced silver concentrations to levels greater than background values that varied, by WWMPP season, from less than 2 to about 5 parts per trillion. This correlation between enhanced precipitation and silver concentration was confirmed in a recent cloud-seeding program in Australia. Silver concentrations from snow samples collected during the WWMPP were quite variable, and at times, were complicated by silver intermixed in dust that is sometimes deposited naturally in the snow. Although silver concentrations during seeding periods were generally lower than those found in Australia, there was success in linking enhanced silver concentrations to RSE case periods in the Medicine Bow and Sierra Madre targets, and to the non-randomized seeding in the Wind River Range. A particularly significant environmental finding was that cloud seeding did not broadly increase the average silver concentration in the snowpack to levels above the pre-WWMPP background concentrations.

Ground-based measurements of silver iodide particles from ground-based seeding were made near the Medicine Bow target snow gauge site with an acoustic ice nucleus counter (AINC) during the first three project years (2008-2009, 2009-2010, 2010-2011). These measurements confirmed that silver iodide ice nuclei reached the intended target when seeding was conducted in the Medicine Bow Range (Boe et al. 2014; Xue et al. 2014), as well as on some occasions when seeding was conducted upwind in the Sierra Madre Range. The latter result had been raised as a possibility by external reviewers of the initial experimental design, and the measurements of AINC were undertaken to address this question from the review. This result has important implications for the RSE, since seeding from the upstream range impacts the ability of the downstream range to serve as a control for the RSE, as specified in the crossover design. Based on these AINC results the seeding operations were changed to allow a longer clearance period between consecutive experimental cases. Nonetheless, at the time the AINC measurements were collected, the impact on precipitation on the downwind barrier was believed to be minimal, although it was understood that it would dilute the magnitude of the response variable.

A University of Wyoming study conducted in parallel with the WWMPP, with funding from the University of Wyoming Office of Water Programs, used an aircraft to study physical evidence of seeding impacts over the Medicine Bows (Geerts et al. 2010). The study estimated up to a 25% increase in precipitation for 7 lightly precipitating storms, a small sample set. Additional funding for such aircraft studies was then obtained from the National Science Foundation for two additional years of measurements, also taking advantage of the cloud seeding opportunities provided by the WWMPP. These subsequent measurements did not replicate the considerable seeding effect observed in the initial sample set, although there was still an overall enhancement in the radar signature in the seeded clouds. These differences between the two studies highlight the difficulties of using a very limited sample set, where the seeded clouds are known *a priori*, to make broad conclusions, and emphasizes the need for randomized blind statistical tests on a large number of seeding cases, such as the WWMPP RSE.

Modeling Studies

High-resolution Weather Research and Forecasting (WRF) modeling studies were conducted using an NCAR cloud-seeding module (Xue et al. 2013a, b) to simulate the seeded cases from the RSE including simulating silver iodide plumes in the model based on actual generator operations during the 2009-2010, 2011-2012, and 2013-2014 seasons. The model was verified using radiometer, snow gauge, and sounding data and shown to perform reasonably well for most of the cases. An important discrepancy in model performance occurred in the timing of supercooled liquid water and affected about one-third of the cases. While not perfect, the model can be used to provide insight into critical questions such as unintended downwind seeding effects and overall seeding impact.

The NCAR cloud seeding module was used to evaluate the impact of seeding by comparing model runs with simulated seeding to "control" runs without seeding for three seasons of the RSE cases. The results indicated that the targets in both mountain ranges experienced simulated seeding effects between 10 to 15%. Although these model simulations are encouraging, a model analysis of the full six years of RSE cases was beyond the scope of the project. If the RSE statistical results could be replicated by modeling the six years of RSE cases, confidence in the model's ability to simulate seeded clouds would be established. This would then allow additional analysis of the physical processes important to the RSE results.

Statistical Studies

Prior to completing the statistical analysis, careful quality control procedures were developed and performed on the snow gauge data by personnel without knowledge of the seeding decisions. A critical component of the program design was that each target and control site had three snow gauges, which provided redundant data for the quality control methodology. Of the 154 RSE cases conducted, 118 were included in the primary statistical analysis after removing 36 cases that did not pass the snow gauge data quality control (23) or did not have the required operational generators available (13).

The primary statistical analysis yielded a RRR of 1.03 and a p-value of 0.28. These results imply a 3% increase in precipitation with a 28% probability that the result occurred by chance. Since the p-value is greater than 0.05, the primary statistical analysis indicated no significant seeding effect. Further analysis, however, suggested that two factors influenced this result: 1) the occurrence of unintended downwind effects on the Medicine Bow by seeding over the Sierra Madre; and 2) insufficient amounts of silver iodide reaching the intended target.

The modeling studies identified 18 RSE cases with unintended downwind seeding impacts on precipitation over the Medicine Bow Range. Eliminating those 18 cases from the snow gauge data set increased the RRR to 1.09. The ground-based AINC measurements indicated that silver iodide reached the Medicine Bow target in 21 Sierra Madre seeding cases. Eliminating these 21 cases from the snow gauge data set increased the RRR from 1.03 to 1.04. We believe these differences result from the fact that the presence of silver iodide at the surface does not necessarily indicate enhanced precipitation. To have an effect on precipitation, silver iodide is needed at cloud level and may not be reflected by a measurement at the surface. In contrast, the model evaluation of downwind impacts was based directly on the differences in precipitation between control and seeded simulations, therefore we would expect the cases eliminated by the model to have a greater impact. These results suggest that unintended downwind seeding of the Medicine Bow by the Sierra Madre cases impacted the primary statistical analysis used to evaluate the project.

The number of seeding generators run per case varied based on wind direction requirements in the final design or on operability of the generators. This resulted in cases having less than the maximum of 32 “generator hours” (the combined number of hours that all operational generators were run, which is proportional to the total amount of seeding agent released per case). When the snow gauge data were stratified by generator hours, the value of RRR increased from 1.03 to as high as 1.17 for the 62 cases that included at least 27 generator hours of seeding. This result suggests that a sufficient amount of seeding agent is necessary to produce a detectable seeding effect.

Because these results were reached through multiple stratifications of the RSE data to achieve a positive result, and used covariates that were not specified *a priori* for the statistical study, these latter results cannot be claimed to be statistically significant. Although for data stratification the p-value cannot be used to claim statistical significance, it can be used to evaluate the strength of a particular stratification of the RSE data. Using such *a posteriori* analysis of statistical data to achieve a desired result is known as multiplicity. While recognizing the statistical issues related to multiplicity, the RSE data were stratified based on reasonable physical considerations, and the results suggest that the primary analysis would likely have indicated a positive seeding response, if these factors were anticipated and accounted for in the experimental design. These stratifications of the RSE data suggest that the primary analysis was impacted by unintended downwind seeding effects on the Medicine Bow as a control during Sierra Madre seeding and by an insufficient number of generator hours for some cases.

Accumulation of Evidence

Combining the results from physical, modeling, and statistical studies provides a way to accumulate "evidence" to develop the assessed seeding effect estimate (Figure 3) following the NRC report guidelines. By far the largest impact on the estimated seeding effect from the statistical results was eliminating cases with low seeding generator hours. This result is consistent with the recent orographic cloud seeding results from Australia that showed, based on *a posteriori* analysis, an increase of ~14% in precipitation as a result of silver iodide seeding when evaluated on the covariate of seeding generator hours greater than a threshold signifying well-seeded cases (Manton and Warren 2011). Without including a generator hour threshold, the primary statistic based on *a priori* analysis in the Australia project indicated a 4% increase, similar to the RSE primary analysis.

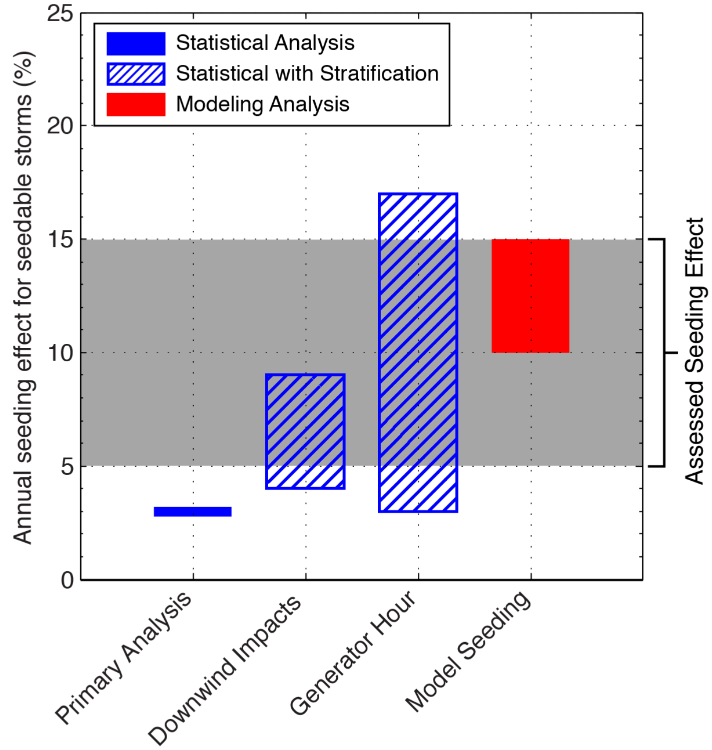

Figure 3. Estimation of seeding impacts on precipitation as determined by various analysis methods. Blue indicates results from the RSE. The solid blue is the primary statistical result, while the hatched blue represent the range achieved through stratification of the statistical data. The red bar represents the range of model seeding results. The accumulation of evidence leads to the assessed seeding effect as indicated by the gray shading.

The accumulated evidence from the statistical, modeling, and physical studies suggests a positive orographic seeding effect, over a winter season, between 5 and 15% in the Medicine Bow and Sierra Madre Ranges, for seedable cases based on the RSE criteria and for which sufficient ground-based silver iodide seeding was achieved (Figure 3).

Climatology of Seeding Opportunities

Because seeding orographic wintertime clouds is appropriate only under certain meteorological conditions, the climatological context for seeding conditions was investigated (Ritzman 2013; Ritzman et al. 2015). The investigation used an eight-year (2000-2008) high resolution regional climate model forced by re-analysis meteorological data (Ikeda et al. 2010) to determine the frequency of seeding opportunities in the Medicine Bow and Sierra Madre Ranges based on the seeding criteria. On average, atmospheric conditions met the seeding criteria less than one-third of the time during the winter, and were accompanied by precipitation approximately half of the time that atmospheric conditions met the seeding criteria. Considering only conditions when precipitation was occurring during seedable conditions indicates, on average, ~30% of the wintertime snowpack over the Medicine Bow and Sierra Madre Ranges for the years 2000-2008 would have been seeded under the conditions specified for the RSE.

Streamflow Impacts

For assessing the potential impacts of seeding on streamflow, hydrological model simulations were performed on the North Brush Creek watershed in the Medicine Bow Range and in the Wind River Range. The North Brush Creek watershed, located in the Upper North Platte River Basin (NPRB), was selected because of the availability of historic unimpaired streamflow data. The Variable Infiltration Capacity (VIC) hydrological model was applied (Oubeidillah et al. 2014), and when compared to observed snowmelt-driven streamflow (streamflow from which the base flow has been subtracted) the baseline VIC model (i.e. no cloud seeding increases) estimated snowmelt-driven streamflow within 1% for the snow melt period 2001-2008. This period was chosen based on the availability of meteorological variables (Ikeda et al. 2010) and identification of seedable storms (Ritzman et al. 2015).

In the Medicine Bow Range, increases in snowmelt-driven streamflow due to cloud seeding were modeled over the range of 5-15%, based on the accumulation of evidence from the WWMPP. Using the frequency of seedable storms determined by the climatology analysis (Ritzman et al. 2015), daily percent increases in precipitation were determined by applying the range of possible seeding percent increase scenarios. The percent increases in precipitation were then applied to daily precipitation data, from the Daymet data base, for use in the VIC model to determine increases in snowmelt-driven streamflow. For a seeding impact of 5-15% on winter precipitation, this resulted in total snowmelt-driven streamflow increases for the North Brush Creek watershed (area 37.4 sq-mi) for the eight-year period of 95 AF/sq-mi to 288 AF/sq-mi. These results were then aggregated to the seedable area in the NPRB within Wyoming. The maximum seedable area, defined as the area with elevation above 9,000 ft, within this region of the watershed was approximately 390 sq-mi. The potential cloud seeding impact area considered was 30 to 80% of the maximum seedable area. The resulting increases in water within the NPRB in Wyoming (see Figure 4) then depends on the increase in precipitation from cloud seeding (5-15%) and the cloud seeding impact area (30-80%) within the watershed. Results from hydrological modeling of the Wind River Range using an un-calibrated version of the WRF-Hydro hydrological model provided results from cloud seeding which were qualitatively similar to those from the VIC hydrological modeling in the North Brush Creek.

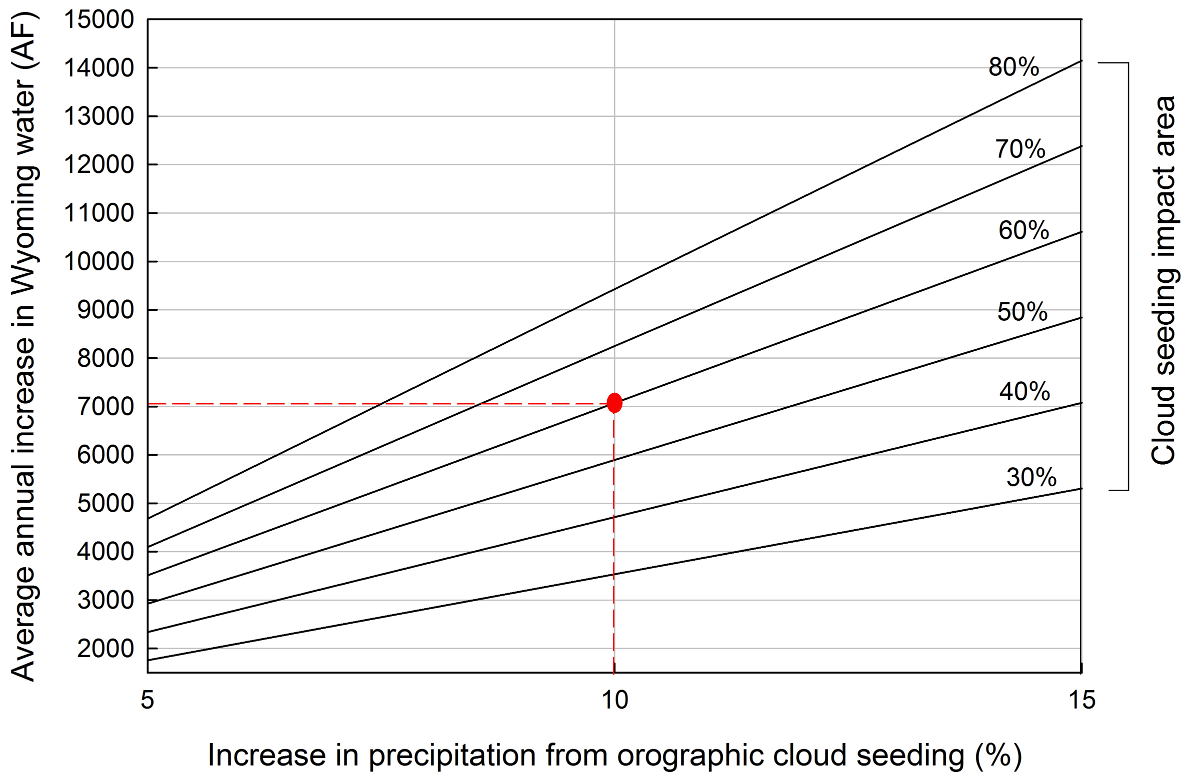

Figure 4. Increases in Wyoming water within the NPRB based on VIC model simulations under the varying estimates of increases in precipitation due to cloud seeding and the various cloud seeding impact area, 30-80% of the maximum seedable area.

To estimate the water generated in the NPRB in Wyoming, the total flow at the Northgate Colorado stream gauge (located immediately south of the Wyoming border) was subtracted from the total flow into Seminoe Reservoir for the period 2001-2008. This resulted in 3.09 x 10^6 AF for 8 years or an average of 390,000 AF per year. This amount does not account for diversions, primarily agricultural, and return flow upstream of Seminoe Reservoir. For a 10% seeding effect impacting 60% of the basin, cloud seeding would generate an average additional 7,100 AF per year, or an increase of 1.8% in streamflow in the Wyoming area of the NPRB. Annual cost estimates for cloud seeding operations are detailed in Table 1. For a purely operational program using remotely controlled ground based generators, the estimated annual costs range from $375,500 to $526,400. The difference results from sponsor-owned and -operated equipment versus a contractor/leased operation plus use of a real-time forecast model. Cost estimates to include an evaluation component are $222,700. Using the low cost estimate and the example of 10% efficiency and seeding 60% of the basin, the cost of water produced would be approximately $53/AF. Figure 5 shows the range of costs for different cloud seeding efficiencies and the range of cost options. For cloud seeding efficiencies of 5-15% and 60% of the area covered the costs are $35-107/AF for the low cost option. A limited amount of North Platte water, if available, is marketed on a temporary year-to-year basis for municipal and industrial uses at $30/AF by the State of Wyoming out of Pathfinder Reservoir, and at $75/AF by the US Bureau of Reclamation out of Glendo Reservoir.

Table 1. Estimated cost scenarios for future Medicine Bow and Sierra Madre operational seeding

Option	***Line Item***	***Description***	***Cost per Season***	***Total Cost Per Season***
Purchase Equipment, Train Personnel to Run the Generators	Ground-based Seeding	16 generators purchase	$190,500	$375,500
	Field Operations/Travel	Staff trained/employed by sponsor	$145,700	
	Maintenance/Off season	Routine maintenance	$8,700	
	Radiometer	Purchase	$30,600	
Lease Equipment, Hire Contractor to Provide Personnel to Run Project	Ground-based Seeding	16 generators lease	$175,800	$420,600
	Field Operations/Travel	Contract staff, per diem and lodging	$192,700	
	Maintenance/Off season	Routine maintenance, per diem and lodging	$26,800	
	Radiometer	Lease	$25,300	
Operational Support	Soundings	44 soundings	$26,400	$80,800
	Real-time High-res Forecast Modeling	Operations and equipment	$54,400	
Evaluation	Precipitation Gauges	4 sites, (8 gauges)	$22,700	$222,700
	High-res Simulation of Seeding Cases	Numerical modeling to evaluate seeding	$200,000	

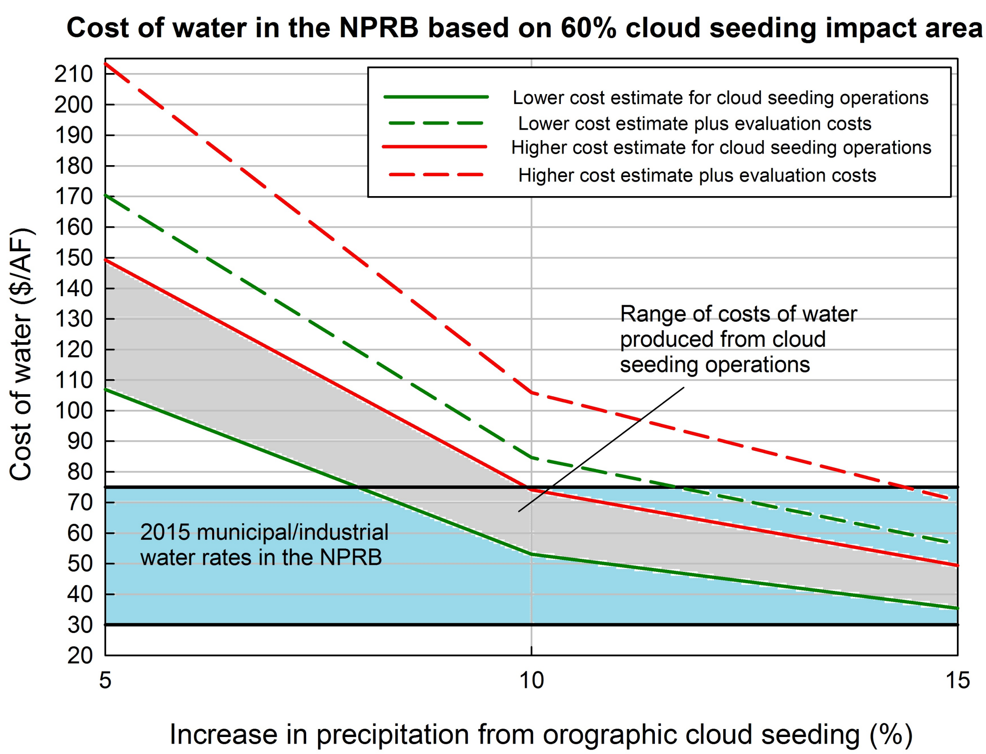

Figure 5. Range of cost per acre-foot of water produced by cloud seeding for the various estimated levels of seeding effect, assuming a cloud seeding impact area of 60% within the watershed greater than 9000 ft, and the range of program cost estimates.

Environmental Impacts of Seeding

Trace chemistry analyses of water and soil samples were conducted for all three ranges following each operational season. These analyses demonstrated a negligible environmental impact of the seeding operations within the three mountain ranges, with silver concentrations in the water ranging in the parts per trillion and concentrations in the soil being in the parts per billion range. These concentrations are far less than would be expected from other potential (background) sources of silver and measured concentrations in water sources were about three orders of magnitude less than values considered hazardous to environmental system or human health.

Extra-area Effects

WRF model simulations were conducted to investigate the simulated extra-area seeding effect from seeding in the Medicine Bow and Sierra Madre Ranges, as well as for seeding in the Wind River Range. Given the observational constraints of the WWMPP, there were no measurements to validate the model beyond the intended seeding target areas, and therefore, these results should be interpreted with the caveat that they were based on model results. The key result from this numerical modeling study is that the net effect of all simulated seeding in areas outside of the intended targets (i.e. extra-area effects) was small to zero (less than 0.5%). This is consistent with previous studies (Long 2001; DeFelice et al. 2014).

Conclusions

The WWMPP provided an assessment of weather modification as a strategy for long-term water management. Specifically, the project was funded to determine whether seeding in Wyoming is a viable technology to augment existing water supplies, and if so, by how much, and at what cost.

The physical evidence from radiometer measurements showed that ample supercooled liquid water existed at temperatures conducive to generating additional snow by silver iodide seeding over the ranges studied. High-resolution and quality-controlled snow gauges were critical to evaluate the effectiveness of cloud seeding and validate the performance of the model used during the WWMPP.

The accumulation of evidence from statistical, physical, and modeling analysis suggests that *cloud seeding is a viable technology to augment existing water supplies*, for the Medicine Bow and Sierra Madre Ranges. While the primary statistical analysis did not show a significant impact of seeding, statistical analysis stratified by generator hours showed increases of 3-17% for seeded storms (Figure 3). A climatology study based on high-resolution model data showed that ~30% of the winter time precipitation over the Medicine Bow and Sierra Madre Ranges fell from storms that met the WWMPP seeding criteria. Ground-based silver iodide measurements indicated that ground-based seeding reached the intended target, and in some cases well downwind of the target. High-resolution modeling studies by NCAR that simulated half of the total number of seeding cases showed positive seeding effects between 10-15% (Figure 3).

In spite of the result of no seeding effect from the primary randomized statistical experiment, ancillary studies, using physical considerations to stratify the RSE data, and modeling studies over full winter seasons, led to an accumulation of evidence from the statistical, modeling, and physical analysis which suggest a *positive seeding effect on the order of 5 to 15%.*

Based on a potential increase in precipitation from seeded storms of 5 to 15%, affecting 30 to 80% of the cloud seeding impact area, the VIC hydrological model indicated an increased streamflow for Wyoming water in the NPRB ranging from 0.4 to 3.7%. Using the lower cost estimate for an operational cloud-seeding program, along with the range of seeding effects and cloud seeding impact areas, the cost of the water ranges from $27 to $214 per acre-foot. Applying the higher cost operational program option with evaluation, the costs range from $53 to $427 per acre-foot.

The NCAR high-resolution cloud model was found to be capable of forecasting the likelihood of seeding conditions over the three mountain ranges studied, aided in the placement of ground-based seeding generators, and assisted in the evaluation of amount and location of seeding-enhanced precipitation and in stratification of the RSE data. The development and real-time application of this model was a major accomplishment of the WWMPP.

Measurements of silver in the snow pack, soil, and streams consisting of snowmelt showed negligible environmental impacts (parts per trillion in the snow and streams). Silver concentrations in the soil were measured in parts per billion indicating it is a much larger source of silver than snow produced by cloud seeding. Silver concentrations in snow are also far less than that expected from other sources, such as industrial waste or large combustion sources. We therefore conclude that winter orographic cloud seeding with silver iodide using the procedures from the WWMPP has a negligible impact on the environment and on precipitation in the area surrounding the intended target.

Recommendations

Based on the results of the WWMPP, *we recommend that the WWDC consider implementation of cloud-seeding technology within the State of Wyoming* by carefully addressing each of the following five components: 1) Barrier identification, 2) Program design, 3) Operational criteria, 4) Program evaluation, and 5) Program management.

1. Barrier Identification
   - Conduct large-scale climatological modeling and observational studies over time scales as long as a decade to identify the barriers most conducive to seeding.
2. Program Design
   - Use the barrier identification climatology and cloud-seeding model to determine whether to use ground or airborne seeding and where to place generators and/or conduct aircraft flights.
   - Perform additional high-resolution modeling studies to test and refine the initial program design and optimize the location and number of generators to ensure that the silver iodide will reliably reach the intended cloud. When siting generators, also consider institutional constraints associated with high-elevation deployments.
   - Based on model analyses and other considerations, determine the sites for the radiometer and sounding units, and identify critical locations for snow-gauge sites.
   - Plan sufficient time to obtain the necessary permits. Siting equipment on Federal lands requires a special use permit, which will include NEPA. Allow 2 to 24 months for permitting activities, depending on the scale of the project. Environmental Impact Statements can take up to 24 months, while State lands permitting in Wyoming can take 1 to 3 months.

- Communicate with land management agencies early and often throughout the permitting process.
- Engage in public information outreach efforts to identify and address environmental concerns and encourage stakeholder involvement.

3. Operational Criteria
   - Use the radiometer, sounding, and high-resolution, real-time forecast model information to identify seeding opportunities.
   - Ensure that generators and other instruments are properly maintained.
   - Consider the implementation of a real-time model that explicitly forecasts seeding opportunities.
   - Suspension criteria must be clearly defined and revisited as needed.
4. Evaluation
   - Model simulations in combination with high-resolution snow-gauge measurements provide a low-cost methodology to evaluate the effectiveness of cloud-seeding programs. Consider this approach to evaluate the seasonal returns on the investment in the seeding program.
   - High-resolution models used to evaluate cloud seeding need to be validated using sounding, radiometer, and snow-gauge data. Therefore, any model-based evaluation approach should include validation with observations.
   - Evaluate the impacts of cloud seeding on streamflow using the output of the high-resolution cloud-seeding model coupled to a high-resolution hydrology model.
   - Measurements of ice nuclei in airborne snow (i.e. AINC measurements) and in the snowpack (i.e. trace chemistry measurements) are valuable ancillary physical measurements to verify the effectiveness of cloud seeding, as well as for evaluating the performance of the cloud-seeding model and extra-area impacts. The costs for this work and the water chemistry below are not included in Table 1.
   - Water chemistry sampling post-season is useful for addressing environmental concerns, though this will be most effective if good inventories of other potential sources of silver within the sampled watersheds are available.
5. Program Management
   - Consult with a Technical Advisory Team to provide guidance to the program.
   - Share program data with affected federal and state resource agencies.
   - Collaborate with other operational weather modification programs.
   - Conduct information and education outreach efforts with local stakeholders.
   - Pursue collaborative funding opportunities for weather modification activities.
   - Conduct any program evaluation independently from program operations.

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Disclaimer

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