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Weather Modification–
Bighorn Mountains Siting and Design Study

Executive Summary

prepared for

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by

National Center for Atmospheric Research
Research Applications Laboratory
3090 Center Green Drive
Boulder, CO 80301

NCAR

Investigators:
Sarah Tessendorf[1], Roy Rasmussen[1], Lulin Xue[1], Courtney Weeks[1], Kyoko Ikeda[1], Jamie Wolff[1], Michelle Harrold[1], Scott Landolt[1], Duncan Axisa[1], Bruce Boe[2], Patrick Golden[3]

[1]Research Applications Laboratory, National Center for Atmospheric Research (NCAR)
[2]Weather Modification International (WMI)
[3]Heritage Environmental Consultants (HEC)

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Executive Summary

A conceptual siting and design study was completed to assess the feasibility of conducting an operational weather modification program targeting the Bighorn Mountains in north central Wyoming.

A review of previous reports indicated that there were previous cloud-seeding activities in the Bighorn Mountains, spanning the period of 1951–1954. Since that time, no additional permits for cloud-seeding operations in the Bighorns were issued. These previous programs utilized ground-based silver iodide (AgI) generators, and most operations targeted clouds in the summer months.

In more recent years, numerous research investigations have improved the understanding of how to use AgI seeding to enhance snowfall in winter orographic clouds. These include the Wyoming Range Phase I and Phase II Feasibility Studies and the Wyoming Weather Modification Pilot Program (WWMPP). These results were reviewed prior to preparation of this report to ensure it remains consistent with the most recent recommendations for cloud-seeding program design. Noteworthy results from the draft WWMPP report are that while the randomized seeding experiment was statistically inconclusive, an accumulation of evidence analysis approach suggested seasonal precipitation increases of 5–15% in seedable storms. It also demonstrated the capability of numerical models to realistically simulate snowfall distributions. Furthermore, a new modeling capability that simulates seeding effects via a cloud-seeding parameterization was developed and applied to estimate seeding effects, but complete evaluation of this new tool has so far been limited by a lack of necessary observations. The results from this program were utilized by the present study.

In the review of previous reports, the various options for cloud seeding were summarized. It was determined that liquid propane seeding would likely not be an efficient option, given it has very spatially-limited impacts due to the need to release it directly in the presence of supercooled liquid water (SLW). In addition, manual AgI generators were determined to be challenging to implement in the region given the limited number of sites where on-site operators reside. For manual generators to be activated and deactivated during the winter months, siting would need to be at lower elevations in the Bighorn River Basin, and the AgI plume would frequently be trapped and unable to disperse over the mountains at these lower elevations.

Climatology of the Project Area

A climatological study of the project area was conducted to determine the characteristics of wintertime precipitation in the Bighorn Mountains and to estimate how frequently meteorological conditions are appropriate for AgI seeding. The climatology analysis indicated that the typical wind regimes in the Bighorn Mountains are westerly to northwesterly, with few easterly (upslope) events on the eastern slopes. The spatial mapping analysis revealed that liquid water content (LWC) most frequently develops on the western and northeastern slopes of the Bighorn Mountains, while the most frequent seeding opportunities occur on the western slopes.

Based on 0–1 km above ground level (AGL) average temperature and LWC criteria, ground seeding had equal or more frequent opportunities than airborne seeding during the November–April wintertime period. When considering additional criteria for ground-based seeding to be able to reach the clouds, ground-seeding opportunities dropped to nearly zero in the eastern and southern regions, and were substantially reduced in the western region. This was due to the frequent occurrence of stable conditions causing the flow of AgI to pass around the Bighorn Mountains rather than go over. The stability limitation issue for ground-based seeding results in airborne seeding potential in the western region to be greater than ground seeding potential (Figure 1).

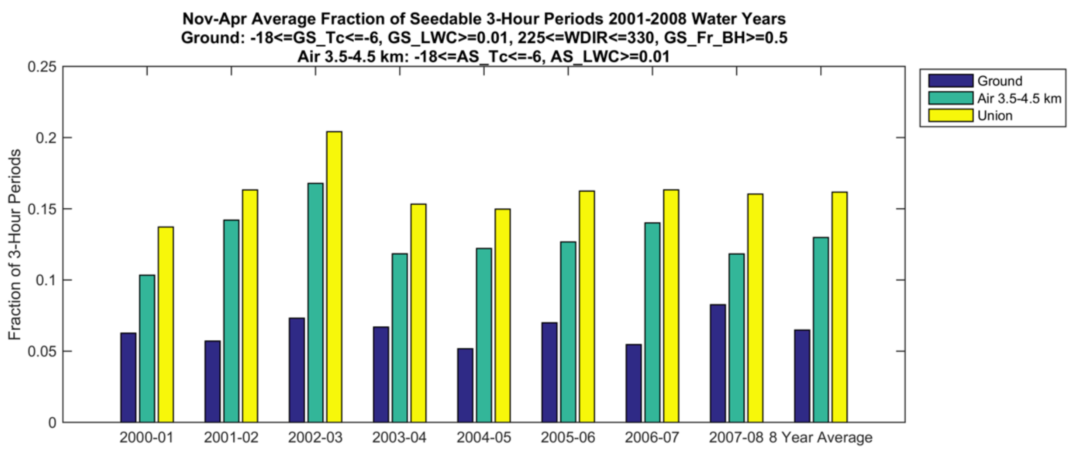

Figure 1. Ground (0–1 km AGL; blue) versus airborne (3.5–4.5 km MSL; cyan) seeding opportunities by November–April season in the western region (fraction of hours in the season that meet the designated criteria, listed atop the figure), and the 8-year average. The frequency of occurrence of cases from the union of both ground and airborne seeding potential is shown in the yellow bar for each time period.

Note that airborne seeding has the additional advantage of allowing seeding in October, May, and June, potentially doubling the amount of seedable precipitation with an aircraft program. However, from a logistical perspective, it is less likely that all airborne "seedable" hours can be seeded, especially with a single aircraft operation, given limited flight and on-station times. Even if the program is restricted to the November–April period, airborne seeding at the 3.5–4.5 km MSL level is likely to yield more seeding opportunities than ground-based operations, considering the stability factors that limit effective AgI transport.

Most of the time when cloud seeding conditions were present, precipitation occurred naturally over the Bighorn Mountains. Study results show that only 19% of the precipitation that fell in a given season was seedable based on the full ground-seeding criteria being met, while 39% of the precipitation that fell in a given November–April winter season was seedable by aircraft.

Preliminary Project Design and Model Evaluation

In order to test a wide variety of program design options, and based upon results of the climatological analysis, several groups of ground-based generator sites were developed. Initially, just five groups of generators were tested, but based on an iterative process with the model evaluation of these design options, a sixth group was also created and tested with the model. The design focused on ground-based seeding and/or airborne seeding with an operational season of mid-November through mid-April (i.e., 15 November–15 April), utilizing AgI as the seeding agent.

Three test cases were simulated to evaluate the impact of the six groups of proposed ground generators and several potential aircraft tracks (Figure 2). The test cases were selected to represent various meteorological scenarios encountered in the Bighorn Mountains, but not every scenario may have been represented by this limited sample. If resources allow, more cases should be tested to obtain more robust results.

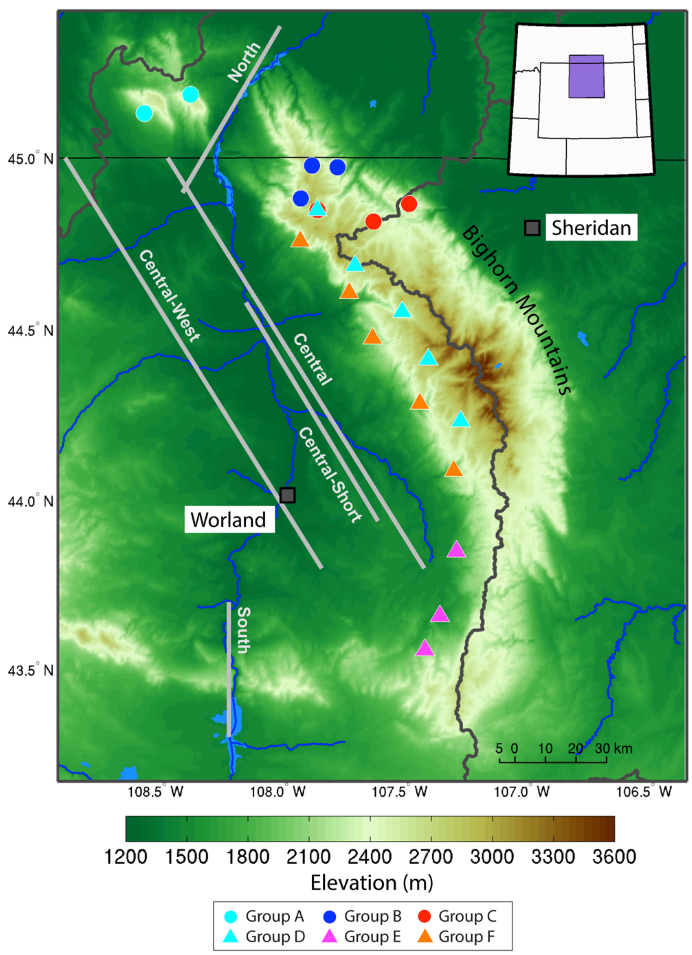

Figure 2. Map of the proposed ground generator groups and potential airborne seeding flight tracks tested with the model.

Based upon the model simulations of the three test cases, ground seeding had very limited spatial impact on the region with Groups A and B rarely impacting the target area.

Group C showed positive simulated seeding effects in some meteorological conditions, especially when the winds had a north-northeasterly component. Groups D and F yielded the best results for ground-based seeding, yet the impact area was rather small and confined to very narrow plumes (Figure 3). Group E ended up being a rather versatile group of generators, given they could impact the southern extent of the Bighorn Mountains under northwest to westerly winds, but could also impact the Cloud Peak area under southwesterly winds. Nonetheless, in the cases that were tested, Group E showed minimal overall simulated impacts (Figure 3).

Airborne seeding tended to yield the most widespread and greatest simulated seeding effects (Figure 3). However, shorter seeding flight tracks are recommended because the shorter central track experiment produced a greater simulated seeding effect more often than the longer track due to the simulated AgI plume being more concentrated using the shorter track length. The benefit of airborne seeding is that it can be performed wherever SLW is present. This can include situations where elevated SLW extends quite far upwind (to the west) of the mountains, as occurred in some of these cases. Airborne seeding is the only way to impact elevated SLW layers over the Bighorn River Basin because the air is often too stable in this valley to use ground generators to reach those higher altitudes. It should be noted that not all of the simulated seeding effects from seeding further upwind impact the higher elevations of the Bighorn Mountains; rather they often broadly impact the Bighorn Basin. Based on the modeled climatology, easterly upslope events include SLW, but occur infrequently. Therefore, due to the lower frequency of occurrence, siting ground generators on the eastern slope of the Bighorns is not advised, but it should be noted that airborne seeding is versatile enough that it can also be used to target easterly upslope events.

A field survey was conducted to assess the suitability of potential generator locations for seeding effectiveness, land access issues, and the impacts of land ownership. During the field survey, many of the originally proposed generator sites were moved short distances to more suitable locations. Six alternate sites were also added, because the original sites were not accessible, or the alternate sites were determined to be better suited for operational deployment. As a result of the field surveys and modeling analysis, a total of 21 generator sites—12 on United States Forest Services (USFS) lands, 5 on Bureau of Land Management (BLM) lands, 3 on private lands, and 1 on State lands—were considered to be viable options from a permitting and operational perspective.

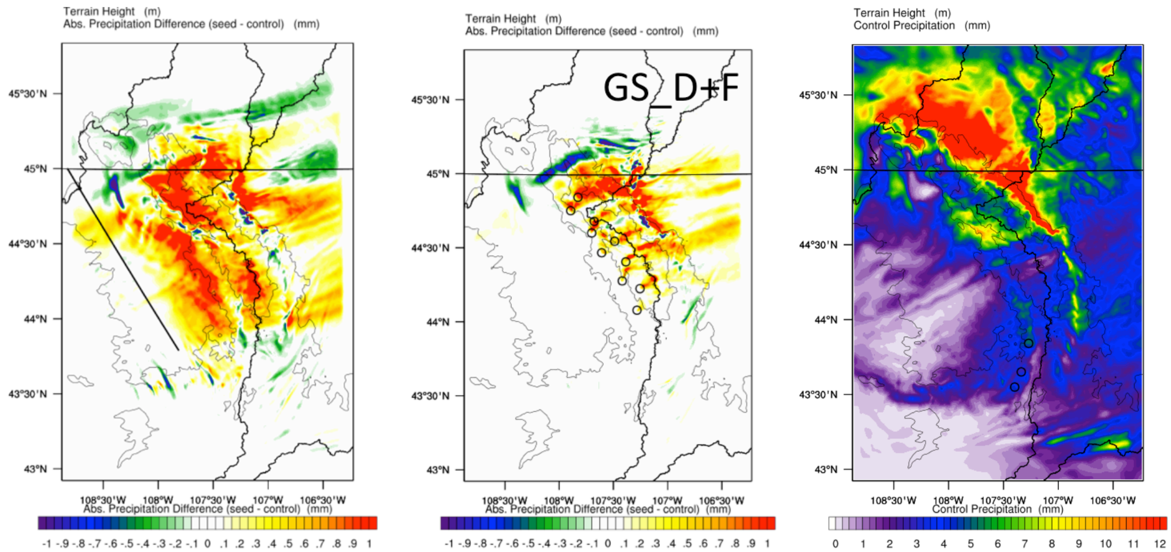

Figure 3. Simulated seeding effects (changes in precipitation, mm) for the 20 November 2007 case from simulated airborne seeding along the Central-West track (left) and ground-based seeding with Groups D+F (middle). The total accumulated precipitation (mm) from the unseeded control simulation is shown on the right.

Operational Criteria and Other Considerations

Operational seeding criteria were developed for possible ground-based seeding operations as well as for potential seeding with an aircraft. Observations to determine when the operational criteria are met are available in real time via a variety of products available on the internet. However, given the dearth of observations in the region, deploying project-specific instrumentation (i.e., radiometer and soundings) or the use of numerical models can play vital roles in making seeding decisions. Other programs in the region, such as the operational cloud-seeding program in the Wind River Range, may provide leveraging opportunities to obtain data from such additional operational tools. Cloud-seeding suspension criteria were also developed based on the criteria developed for the Wind River Range operational program.

Common questions regarding the implementation of a cloud-seeding program are concerned with possible extra-area effects of cloud seeding on precipitation, and possible environmental impacts of the cloud-seeding agent (AgI). Recent studies on these topics were reviewed, including the most recent WWMPP study. These studies concluded that seeding effects outside of the intended target area would be negligible, and that no environmentally harmful effects would occur from the use of AgI as a cloud-seeding agent.

Potential Benefits and Benefit/Cost Analysis

Estimates of streamflow changes due to seeding impacts were calculated using preliminary results from the WWMPP, which were based on three levels of estimated seasonal seeding effects of 5, 10, and 15% in seedable storms. The remaining parameters needed to calculate seeding impacts are the percentage of seasonal precipitation that occurs during seedable conditions, the target area coverage of the seeding effects, and the ratio of increase in streamflow relative to an increase in snowpack. The seasonal seedable precipitation was determined from the climatological analysis for the Bighorn Mountains, while the target area coverage was assumed to vary between 30–80%, substantiated by the model simulations. Estimates of streamflow input into the Bighorn and Powder/Tongue River basins from the Bighorn Mountains were determined using the 8-year Weather Research and Forecasting (WRF) CONUS model simulations, since other estimates provided in local water plans were not specific to drainage solely from the Bighorn Mountains. These model estimates indicated average April–July streamflow from the Bighorn Mountains into the Bighorn Basin is approximately 515,000 AF and into the Powder/Tongue River Basin is roughly 465,000 AF. The streamflow estimates from the local water plans and the model simulation agreed relatively well. The ratio of increase in streamflow relative to an increase in snowpack was estimated to be 0.49 using the WRF CONUS model-simulated snowpack compared to simulated runoff. This ratio accounts for the evapotranspiration of some of the additional snowpack from cloud seeding.

Average estimates of streamflow increase (April–July runoff increase from seeding) based upon the parameters described above and combined across the two river basins produced estimates of streamflow increases ranging from ~1,400 AF to ~10,900 AF for ground-based seeding depending on the level of the estimated seeding effect and the assumed area of seeding coverage (Figure 4). Assuming a 50% area coverage of seeding effects, the range for ground-based seeding was between ~2,300 AF to ~6,800 AF (based upon the 5–15% assumption of seasonal seeding effect in seedable storms). These values were used in the benefit/cost analysis. For airborne seeding, which had a much higher fraction of seedable precipitation from the climatological analysis (i.e., 39% compared to only 19% for ground seeding), the estimates of streamflow increases ranged from ~2,800 AF to ~22,500 AF, depending on estimated seeding effect and area of coverage. However, limited aircraft on-station time was not accounted for in the fraction of seedable precipitation calculation, which for a single aircraft operation could conceivably limit the frequency of time that can be seeded in a given season. Nonetheless, assuming a 50% area coverage of seeding effects from airborne seeding, the range of estimated additional streamflow was between ~4,700 AF to ~14,000 AF. These values were used in the benefit/cost analysis.

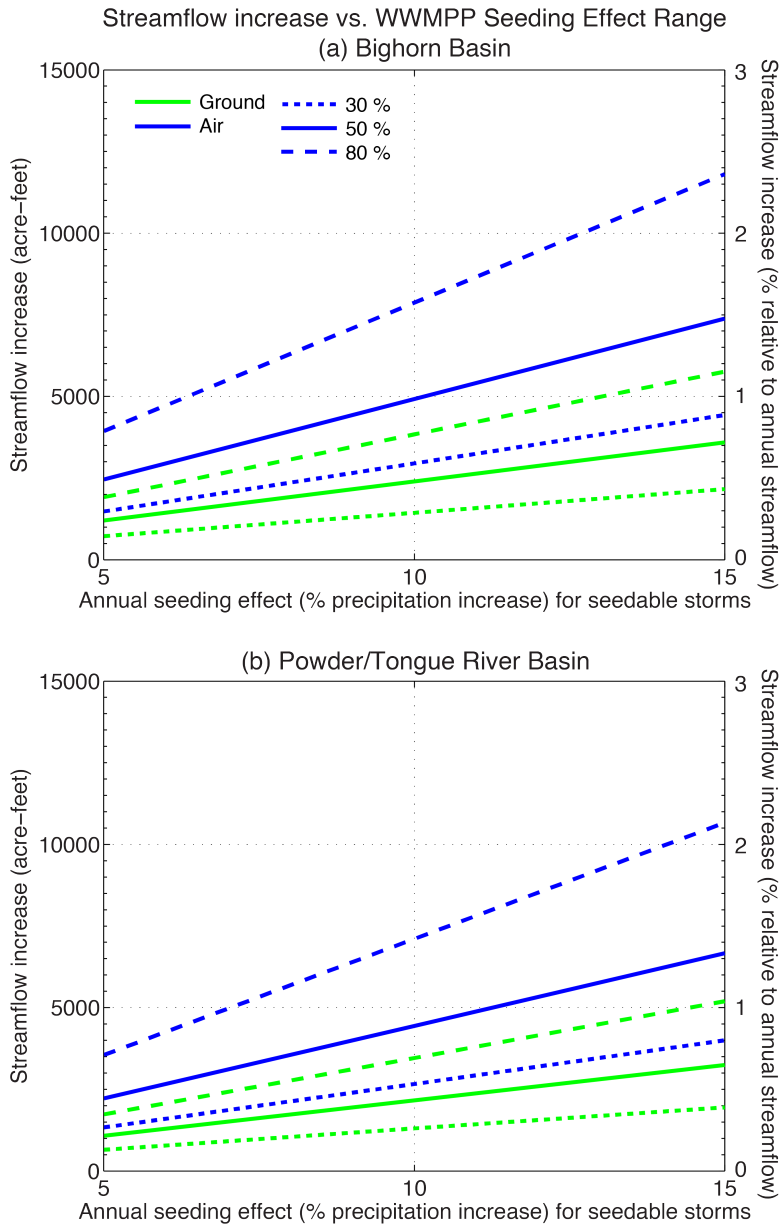

Figure 4. Estimates of streamflow increases in acre-feet (left ordinate) and percent increase relative to annual streamflow (right ordinate) into (a) the Bighorn River Basin and (b) Powder/Tongue River Basin using the levels of seasonal seeding effects for seedable storms from the draft WWMPP report (5, 10 15%). The streamflow calculations include adjustments to relate the seeding effects to total target area precipitation, which requires an estimate of target area seeding coverage. The streamflow estimates for the various levels of area coverage (30-80%) are denoted by the different line styles. Different line colors represent the estimates based on a ground-based (green) or an airborne-based (blue) seeding program. The 50% area coverage (solid lines) is used for streamflow estimates assumed in the benefit/cost calculations.

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

1) A program with 15 remote-controlled ground-based generators (estimated annual cost: $479,655), and
2) A single, stand-alone aircraft seeding program (estimated annual cost: $352,421).

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 to determine whether the program would be considered feasible. These Guidelines have two basic considerations: is the program technically feasible, and is the proposed program economically feasible? An affirmative answer to both questions is required in order for the program to be considered feasible. The evidence presented in this study is that the program is technically feasible.

For a proposed program to be economically feasible, the ASCE Guidelines recommend that a proposed program have an estimated benefit/cost ratio of 5/1. Several assumptions were made concerning the possible benefit/cost ratios for the proposed program (e.g., allocation of the water, value of the water, etc.). At the assumed costs of water ($30–$50 per AF), neither seeding program option yielded the 5/1 ratio with the assumed area impact of 50% (Figure 5), nor when assuming an 80% impact area. As a result, this proposed program would not be economically feasible based upon the ASCE Guidelines. Of the two seeding program options (ground or airborne), airborne resulted in a higher benefit/cost ratio than ground, given the lower cost of the airborne program and the higher amount of seedable precipitation for airborne seeding found in the climatology analysis. Sharing operational resources with another nearby cloud-seeding program might reduce costs and make a cloud-seeding program in this region more cost effective; however, it is beyond the scope of the present study to make this determination.

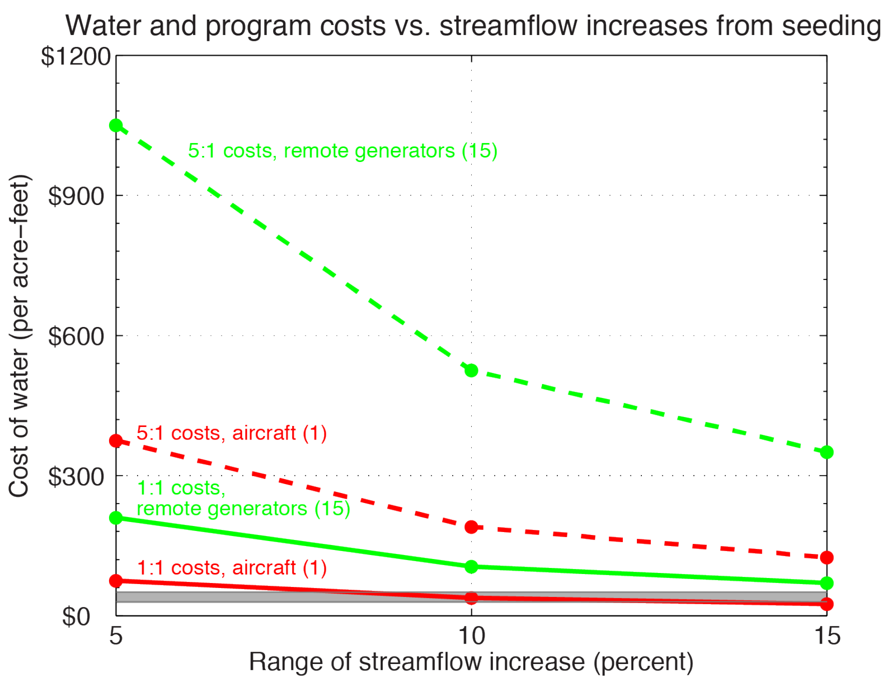

Figure 5. Cost of water for usage categories and for two estimates of annual seeding program costs for the three levels of estimated streamflow increases resulting from WWMPP annual seeding effects for seedable storms. Gray shading indicates estimated water costs. The solid green and red lines indicate the cost for the 15 remote generator ground-seeding option versus the single aircraft airborne seeding option, respectively, expressed as program costs per acre-feet 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.

Conclusions and Recommendations

This study concludes that it is technically feasible to develop an AgI cloud-seeding program to target the Bighorn Mountains. This is supported by the climatological analysis and model evaluation, as well as radiometer measurements collected over the winter of 2015–2016. Ground-based cloud-seeding opportunities are less frequent due to the complex terrain that limits siting generators in locations that will effectively disperse the AgI plumes over the mountains. Opportunities for airborne seeding are more frequent and promising. Numerical simulations of airborne cloud seeding in the three tested cases indicated that airborne seeding is far more effective than ground-based seeding for enhancing precipitation both over the mountains and upwind of the mountains. However, it is important to note that three cases is not a large enough sample to draw robust conclusions, and therefore additional cases would be needed to thoroughly assess this recommendation.

The study also concludes that the program is not economically feasible based upon the ASCE guidelines. The cost effectiveness of a cloud-seeding program is dependent on several factors, including the benefit/cost ratio desired, actual water costs, and the level of seeding effect achieved. The benefit/cost analysis indicated that an airborne seeding program (~$25–75/AF) targeting the Bighorn Mountains was more cost effective than a ground-based program ($70–210/AF). The implementation of a collaborative weather modification program to share an aircraft, staff, and/or other operational resources (e.g., observations and forecast models) might yield the most cost-effective opportunity for a cloud-seeding program in this region; however, it is beyond the scope of the present study to make this determination.

The recommendations based on the results of this study are provided below. Given the complexity of the terrain and short duration of the study, only a few representative cases were evaluated in this study. To increase confidence in the results, it is recommended that additional studies be conducted with the atmospheric model coupled to a hydrological model. Specifically:

- Additional test cases (ideally an entire season of seeding cases) should be simulated to better represent the wide variety of storm types and/or the seasonal seeding impacts from seeding with a proposed operational design.
- A spatially-distributed hydrological model coupled to the WRF cloud-seeding simulation output should be run for multiple winters to better estimate hydrological benefits of cloud seeding. This modeling system would utilize the 3D spatial distribution and magnitude of the model-simulated seeding effects on snowpack to drive the hydrological model, which would calculate the water balance and routing of the streamflow driven by the snowmelt for every basin in the domain, obviating the need for fixed assumptions across the domain.

Recommendations specific to the design and implementation of an operational cloud-seeding program in the Bighorn Mountains include:

- Seeding should be conducted using AgI as the seeding agent.

- The seeding season should be November–April for ground-based seeding, but could be extended from October into May or June if airborne seeding is utilized.
- The climatology analysis and cost estimates indicate that airborne seeding has the potential to be more cost effective than ground-based seeding. Therefore, airborne seeding is recommended.
- If airborne seeding is implemented, shorter aircraft tracks should be used to achieve better coverage of AgI over the target area. In particular, the central track, using an altitude where the maximum LWC resides, was found to give the best result.
- Basic seeding criteria should be based on readily available (and quickly accessible) meteorological data. Given the lack of regular meteorological observations in the region, 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 have not been considered in the present benefit/cost analysis.
- In order to reduce costs, opportunities to share resources (especially an aircraft) with other nearby cloud-seeding programs should be explored. Specifically, a climatological analysis should be conducted to determine if the timing of seedable storm systems would allow for cost effective resource sharing (i.e., utilizing a single aircraft to target multiple mountain ranges).
- If the State of Wyoming were to operate multiple cloud-seeding programs across the State, it is recommended that a real-time forecast modeling system be implemented statewide to provide guidance on whether passing storm systems are suitable for seeding. A forecast modeling system would generate a cost savings by identifying when storms have high seeding potential, therefore maximizing cloud seeding impacts and avoiding seeding of cases with only limited potential. The model can also serve as a basis for seasonal program evaluation.

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