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# Weather Modification Feasibility – Wyoming Range Level II Phase II Study

**Executive Summary prepared for**

**Wyoming Water Development Commission**
**State of Wyoming**

by

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# Executive Summary

A Level II, Phase II Feasibility Study was completed to assess the feasibility of conducting an operational weather modification program targeting the eastern slopes of the Wyoming Range in western Wyoming. This study followed a Level II (Phase I) Feasibility Study that was completed in 2006 by North American Weather Consultants (NAWC). The Phase I Feasibility Study focused on the potential for operational cloud seeding in the Salt River and Wyoming Ranges. Since then, Idaho Power Company (IPC) expanded their operational cloud seeding program into the region, particularly the western slope of the Salt River Range targeting the Snake River Basin. The Wyoming Water Development Commission (WWDC) funded the Level II, Phase II Feasibility Study in order to reexamine operational cloud seeding opportunities in the region, in light of the recent developments by IPC and with a renewed focus on targeting the eastern slopes of the Wyoming Range to enhance streamflow into the Green River Basin. This Phase II study was led by the National Center for Atmospheric Research (NCAR) with collaboration from NAWC and Sunrise Engineering.

Sixteen tasks were identified by the WWDC for the study, including: scoping and project meetings; reviewing previous studies and data; climatological analysis of the project area; development of a preliminary project design; model evaluation of the project design; field surveys of potential ground generator locations; assessing the access/easements and permitting/reporting for potential generator sites; operational criteria development; a review of environmental and legal implications; potential benefits analysis; cost estimates; development of a cost/benefit analysis of the potential program; writing reports; giving presentations on the final results; and climatological monitoring of the study area.

Previous cloud seeding programs in the region relevant to the feasibility and design of an operational cloud seeding program targeting the Wyoming Range were reviewed. Two primary programs of relevance are the IPC cloud seeding program that has recently expanded into western Wyoming and the Wyoming Weather Modification Pilot Program (WWMPP) that was recently completed in the Medicine Bow and Sierra Madre Ranges in southern Wyoming. The results from randomized seeding experiments, evaluations of operational programs, and descriptions of observational and modeling studies were included. Noteworthy results from two randomized seeding experiments recently concluded seasonal increases of 5-15% in seedable storms from the preliminary WWMPP results (which translates to a target area average of 3-9%, assuming a 60% impact area) and a target area average seasonal increase of 13-14% for seedable storms from the Snowy Mountains program in Australia. An evaluation of streamflow in sub-basins around the long-running operational program near Vail, Colorado showed ~10% median increase in annual streamflow (with a range of 6-29%) for well-seeded sub-basins. The WWMPP and IPC programs also demonstrated the capability of numerical models to simulate realistic distributions of snowfall as well as including simulated seeding effects via a seeding parameterization.

Orographic cloud seeding (in mountainous regions) aims to enhance precipitation in winter storms with an inefficient precipitation process due to a lack of natural ice nuclei. This inefficiency allows supercooled water (water droplets in liquid state at temperatures below freezing) to persist for long periods instead of being depleted by ice crystals, which grow and fall as snow. In contrast to natural ice nuclei, artificial ice nuclei, such as silver iodide, will nucleate substantial numbers of ice crystals at subfreezing temperatures of −6 °C (+21 °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 most basic environmental conditions needed for an operational orographic cloud seeding program to seed storms are temperatures cooler than −6 °C and the presence of supercooled liquid water in the orographic clouds. Numerous studies have indicated that supercooled liquid water is often present in winter orographic clouds. Additionally, the silver iodide needs to be released in a manner that will transport it into these suitable clouds. Orographic cloud seeding typically uses ground-based generators to produce a silver iodide plume, which requires the environmental conditions (i.e. wind direction, atmospheric stability) to be conducive to transporting the silver iodide into the orographic clouds. Another method for releasing silver iodide is with a seeding aircraft, which disperses the silver iodide directly into the cloud along the flight path. This manner of silver iodide release is less dependent on wind direction and stability conditions, given that the flight path can be tailored to the wind direction for each case, and that silver iodide is being released directly into the cloud at temperatures where immediate nucleation may occur.

**Climatology of the Project Area**

A climatological study of the project area was conducted to determine the characteristics of wintertime precipitation in the Wyoming Range region and estimate how frequently environmental conditions would be amenable to seeding. The study utilized three years of observations recently collected in the region by IPC and results of an 8-year high-resolution model simulation over the region.

The typical winds during winter storms impacting the Wyoming Range blow from the west to northwest and occasionally from the southwest. Easterly upslope events on the eastern slopes of the Wyoming Range were very rare, and/or did not produce much, if any, precipitation. Moreover, a spatial mapping analysis of the 8-year model output revealed that liquid water was rarely located over the eastern slopes of the Wyoming Range, and therefore the study concluded that the most feasible conditions for cloud seeding were on the western slopes of the Wyoming and Salt River Ranges. With the goal of targeting precipitation enhancements on the eastern slope of the Wyoming Range, the study then focused on a design that would seed storms that met seeding criteria along the western slopes of the Ranges, but that produced additional precipitation spilling over onto the eastern slope of the Wyoming Range.

The months identified as having the most frequent opportunities for cloud seeding were the winter months of November through April, with the December through March period having the highest frequencies. The observational analysis confirmed that notable periods of liquid water meeting the temperature criteria typically occurred in the November–April months. The model-based analysis of ground seeding opportunities suggested that 28% of the wintertime months (November–April) met the basic temperature and liquid water criteria.

Based on the observational analysis, atmospheric stability would likely only limit the transport of silver iodide plumes released from valley floor ground generators in approximately one-quarter of cases that met the temperature and liquid water criteria. The model-based analysis, that included Froude number for assessing the potential for dispersion of silver iodide over the mountain barrier from ground-based generators and also included a wind direction restriction, showed that the fraction of seedable wintertime hours was reduced by about one-third from using just temperature and liquid water criteria to also including stability and wind direction, resulting in 19% of the total hours in a typical winter season being seedable by ground-based seeding.

The potential for airborne seeding was also assessed for two layers in the atmosphere: 3–4 km above mean sea level (MSL) and 4–5 km MSL based on minimum flight altitudes in the region. Only the temperature and liquid water content criteria were assessed for these layers because aircraft seeding is less impacted by wind direction and stability. The 3–4 km MSL layer met the seeding criteria 23% of the winter season, while the criteria were met only 7% of the season in the 4–5 km MSL layer due to the higher layer having less supercooled liquid water and occasionally being too cold. Airborne seeding potential at 3–4 km MSL had similar frequencies as ground seeding (Figure 1). A combined airborne and ground program could yield roughly 40% more cases per season relative to a ground-based program alone, totaling 27% of the season being seedable (Figure 1). Nonetheless, 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 on station times.

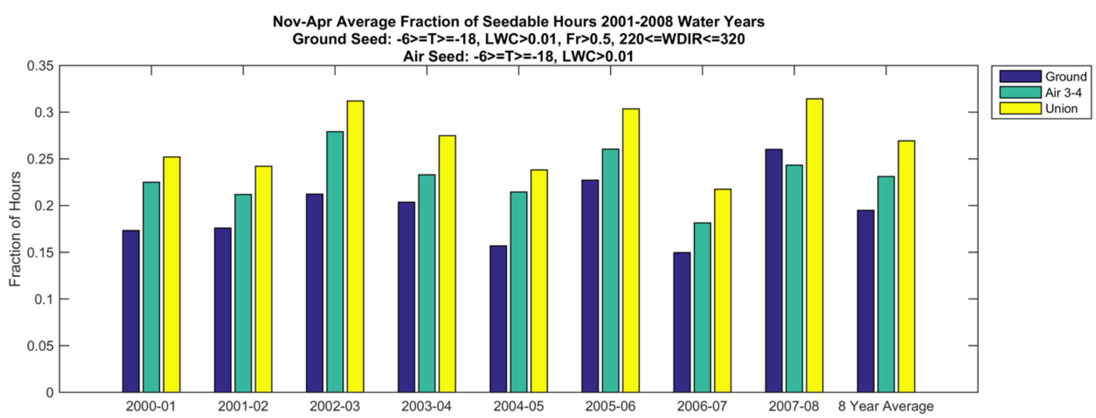


**Figure 1. Ground (0–1 km AGL; blue) versus airborne (3–4 km MSL; green) seeding opportunities by Nov–Apr season (fraction of hours in the season that met the designated criteria, listed atop the figure), and the 8-year average. The frequency of occurrence of cases from the union of both ground and airborne seeding potential is shown in the yellow bar for each time period.**

Approximately half to two-thirds of the time when cloud seeding conditions were present, precipitation occurred over the Wyoming Range. This indicates there are some situations with very low precipitation efficiency in which cloud seeding could have potential benefits. Roughly half (47%) of the precipitation that fell in a given season was seedable based on ground-seeding criteria being met. Nearly two-thirds of the precipitation that fell in a given winter season was seedable by airborne seeding despite similar frequency of airborne seeding opportunities compared to ground.

**Preliminary Project Design and Model Evaluation**

Based on the results of the climatological analysis, the preliminary project design was developed via an iterative process in which the model was used to evaluate the effectiveness of the design. Specifically, each version of the design was evaluated using the Weather Research and Forecasting (WRF) model coupled with a cloud seeding parameterization that simulates the impact of cloud seeding on precipitation. The simulation results of each iteration of the design then informed changes to the next version of the design in order to optimize horizontal coverage and magnitudes of the potential precipitation enhancements over the target region. The target region was defined to be the eastern slope of the Wyoming Range encompassing the Green River Basin above 8000 ft MSL (2438 m). This area is approximately 2080 $km^2$ (803 square miles) and lies within Sublette and Lincoln Counties.

A field survey consisting of visits to potential generator locations was carried out to assess the suitability of each site for seeding effectiveness, any access issues, and the impacts of land ownership. All of the potential manual generator sites were visited, and a few of the remote generator sites that were readily accessible. Several manual generator sites were eliminated or their locations altered based on 1) close proximity to IPC proposed generators, 2) poor exposure due to surrounding terrain, and 3) ownership issues (no occupants or reluctant owners). Siting manual generators in the southern portion of the region was particularly difficult. One remote generator site was adjusted for better access, but since all of the remote generator sites (excluding the IPC generators) are located on United States Forest Service (USFS) land, limited access and permitting requirements become important considerations.

The design focused on ground-based seeding and an operational season of November through mid-April (e.g. 1 November – 15 April), utilizing silver iodide, or more specifically, a silver iodide-salt compound as the seeding agent. Given that IPC operates a network of remote-controlled ground generators west of the Salt River Range, the design was based upon this existing (or soon-to-be implemented) network. In the region of this study, that network consists of nine (existing and/or planned) IPC-owned and operated remote-controlled generators. Besides the remote generators, IPC operates instrumentation and runs numerical models in their program that would be highly beneficial to a Wyoming Range seeding program. Model simulations were run on four test cases, selected to represent a representative variety of storm conditions in the region. The results of model simulations utilizing the network of nine IPC remote generators alone indicated that the IPC network might be quite effective in impacting the eastern slopes of the Wyoming Range (i.e. via a spill-over effect; Figure 2a). Airborne seeding simulations were also conducted and showed similar simulated increases in precipitation as the ground-based seeding scenarios.

The final model evaluation of the design simulated the addition of four additional remote generators to the IPC network (total of 13 remote generators), compared to the addition of five manual generators (9 remotes and 5 manuals), and a combination of the two (13 remotes and 5 manuals). These additional generators were sited to fill in gaps in the IPC network and specifically target the eastern slopes of the Wyoming Range to improve the coverage and magnitude of simulated seeding effects in the target region and were based on feasible sites as determined by the field surveys. These results indicated that both sets of options resulted in similar additional gains for the target region, although the majority of the impacts came from the initial nine remote generators. Moreover, in order for the manual generators to be as effective as the remote generators, the manual generators had to be operated at a higher seeding rate (~22-25 g $h^{-1}$) than is often used in operating such generators.

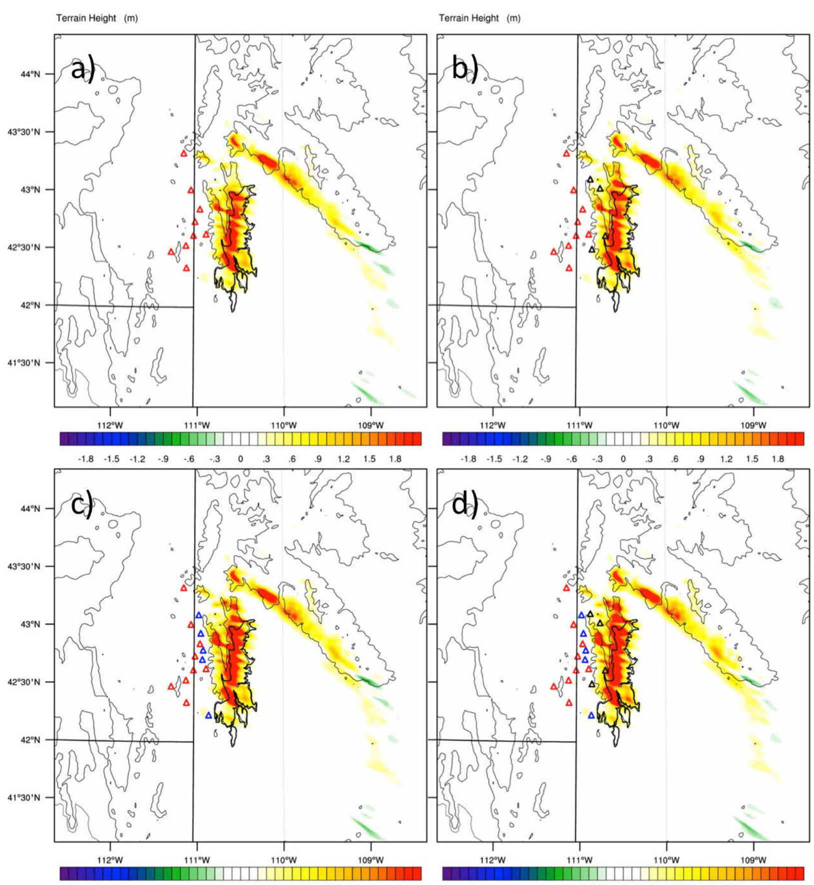


**Figure 2. Model-simulated seeding effects on precipitation (mm) from one of the four test cases (10 January 2014) for the four scenarios evaluated: a) IPC's network of 9 remote generators in the region (red triangles), b) IPC's network plus four additional remote generators (black triangles), c) IPC's network plus five additional manual generators (blue triangles), and d) all three sets of generators combined. Topography contours are included in thick black contours and the target region is outlined as a thick black contour.**

The development and assessment of the project design, especially the determination of simulated seeding effects, relied on simulations of a very limited number of test cases (seeded storms). While these test cases were selected to represent various regimes identified in the climatology analysis, they may not fully represent the climatology of potentially seedable storms. Moreover, these simulations were conducted using a model from which the simulated seeding effects cannot be thoroughly evaluated. These caveats need to be considered when interpreting these results.

Policy considerations, as well as scientific results, may need to drive adjustments to the seeding generator placements. For example, the priority may be high for adding generators targeting the northern half of the Wyoming Range where water shortages for irrigation are critical, or additional generator locations in between the Salt River and Wyoming Ranges may be desired to enhance the seeding effect due to spill-over into the Green River Basin.

**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 numerical models tailored to the region would be beneficial to determine seeding cases. Other programs in the region, such as those operated by IPC and/or the Wind River Range operational cloud seeding program, may provide leveraging opportunities to obtain data from such additional operational tools.

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 (silver iodide). Recent and relevant studies on these topics were reviewed, including the most recent WWMPP study, and the conclusion reached was that seeding effects outside of the intended target area were negligible and there were no environmentally harmful effects of the use of silver iodide 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 in seedable storms of 5, 10, and 15%. The remaining parameters needed to calculate seeding impacts are the percentage of seasonal precipitation that occurred during seedable conditions, which was determined from the climatological analysis for the Wyoming Range, and the target area coverage of the seeding effects, which was assumed to vary between 50-80%. Streamflow estimates of Wyoming Range input into the Green River Basin were largely determined from data in the 2010 Green River Basin Plan. Although the streamflow estimates ranged over a factor of three or more, average estimates of streamflow increase (April-July runoff increase from seeding) combined with the parameters described above produced estimates of streamflow increases ranging from ~3,000 acre feet (AF) to 15,000 AF depending on the level of the estimated seeding effect and area of seeding coverage (Figure 3). Assuming a 70% area coverage of seeding effects, the range was between ~4,400 AF to ~13,000 AF, which is what was used in the benefit/cost analysis.

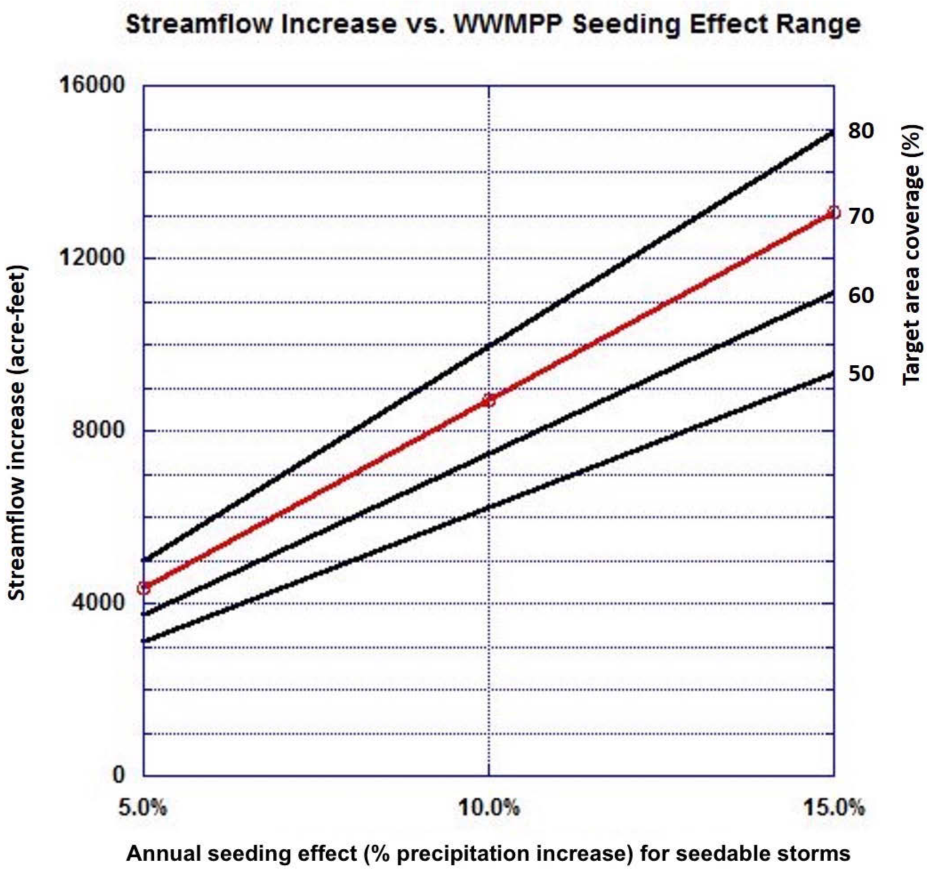


**Figure 3. Estimates of streamflow increases into the Green River Basin using the levels of seasonal seeding effects for seedable storms from the draft WWMPP report. The streamflow calculations include adjustments to relate the seeding effects to total target area precipitation, which requires an estimate of target area seeding coverage. The streamflow estimates for the various levels of area coverage (50-80%) are denoted by the different lines. The 70% area coverage (red line) is used for streamflow estimates assumed in the benefit/cost calculations.**

The complexity and spatial variations of streamflow response to increased precipitation requires an alternative to the relatively simple techniques described to better estimate streamflow changes from snowpack enhancement due to seeding. Implementing a coupled hydrological system, specifically the WRF-Hydro system, along with an atmospheric model that includes a seeding module is one such option that was described in this study that should be considered for further analysis. This option would also require the collection of verification data for use with the model. Both the detailed hydrological analysis and the additional hydrological data would help with the Upper Green River Basin planning process.

Cost estimates were prepared for three different seeding options: 1) a stand-alone program that employs five manually-operated ground-based generators (estimated annual cost:

$121,950), 2) a program with remote-controlled ground-based generators based upon the IPC network of nine (planned and existing) generators, as well as an option for the costs to augment the five existing IPC generators with the addition of four more to complete the network of nine (estimated annual cost: $194,625 or $86,500, respectively), and 3) the addition of a stand-alone seeding aircraft program (estimated annual cost: $367,700). The cost estimates for the first option with the addition of five manual generators, were made as a stand-alone program. It may be more cost effective to add these generators to the manual generator network being operated by the Let It Snow organization that is currently operating a network of manual generators in partnership with IPC upwind of the Salt River Range, and have them operate and maintain these additional generators. The third option for the aircraft program would become more economical by cost sharing with IPC.

A preliminary benefit/cost analysis was performed using the estimate of enhanced average April – July runoff values (4,400, 8,700, and 13,000 AF). American Society of Civil Engineer's (ASCE) guidelines were considered to determine if 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 preponderance of the evidence presented in this study is that the program is technically feasible.*

For a proposed program to be economically feasible, the ASCE recommends 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.). Of the possible seeding options and the three levels of seeding effects, the only one that yielded an estimated 5/1 ratio was the addition of four remote-controlled ground generators to IPC's existing five-generator network when the seeding effect (seasonally relative to seedable storms) was greater than 10%, which thereby assumes IPC would continue to operate its current program with the existing five generators. These results are summarized in Figure 4, comparing water costs under different assumptions, such as water usage, seeding impact on streamflow, and estimates of seeding program costs.

Based on this analysis, the most cost-effective approach is to partner and collaborate with IPC, perhaps including four remote generators sited on USFS lands that would impact the Green River Basin and also impact the Snake River Basin (the target of IPC's operations). This scenario would require permitting under the National Environmental Policy Act (NEPA) process and associated costs. Airborne seeding should not be ruled out if it can be leveraged with an IPC component. The benefit/cost analysis shows that any additional components to a basic program (e.g., specific modeling support or the addition of project-specific observational systems) while desirable, will likely not be economically feasible at the 5/1 level unless cost-shared with other programs in the region.

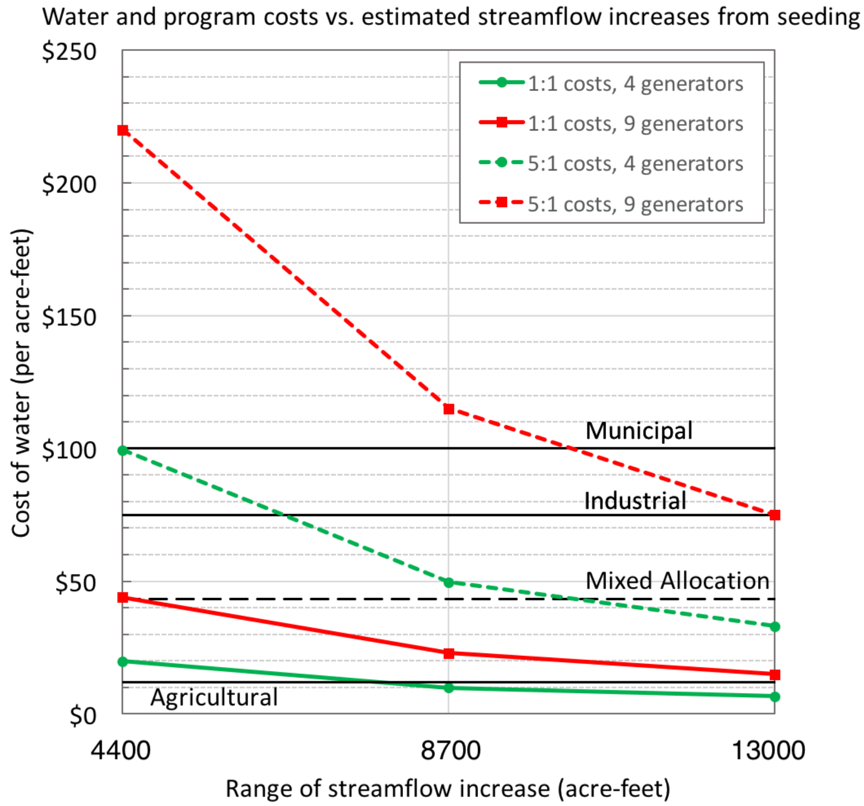


**Figure 4. Cost of water for usage categories and for two estimates of annual seeding program costs for three levels of estimated streamflow increases. Solid black lines indicate water costs for Municipal, Industrial, and Agricultural usages, and the dashed black line is the value using allocations of the three usage categories for the Green River Basin. The solid red and green lines indicate the cost for all nine remote generators ($194,625) versus just four remote generators ($86,500) expressed as program costs per acre-feet of streamflow increase (essentially a 1:1 ratio). The dashed red and green lines show the corresponding 5:1 ratios of water costs to program costs. When the 5:1 ratio line approximates or falls below the dashed black line, a seeding program is considered to be "economically feasible".**

## Conclusions and Recommendations

This study concludes that *an operational cloud seeding program would be feasible to target the east slope of the Wyoming Range* with streamflow increases into the Green River Basin. The basis for this conclusion is from the climatological analysis, model evaluation, and benefit/cost estimates. The analysis indicated that the existing IPC program is already effectively enhancing precipitation in the Green River Basin, and that further enhancement could be achieved by judicious placement of ground based generators and/or airborne seeding.

The IPC weather modification program includes observational data collection and numerical modeling in the region, and thus provides opportunities for leveraging. Based on the synergistic combination of IPC and state of Wyoming resources for this region, it is recommended that a memorandum of understanding or a cost-sharing contract arrangement be established between IPC and the state of Wyoming.

*Collaboration with IPC would allow for a cost-effective process of adding resources in the interest of both parties that may expand seeding opportunities or seeding impacts, such as an airborne seeding component or additional generator sites.*

The specific operational recommendations for the design and conduct of the program are:

- The seasonal period of November to April is the recommended period for the operations based on the presence of seedable storms.
- Silver iodide seeding is the recommended seeding agent.
- Ground-based generators are recommended given they are the most cost-efficient method. Specifically, the addition of four remote-controlled generators to an existing five remote-controlled generator IPC network in partnership with IPC would be the most cost effective option for the State of Wyoming. This addition should be arranged as a cost-share between IPC and the State of Wyoming in order to achieve the most cost effective solution for the State of Wyoming.
- Potential cost-sharing opportunities with other entities involved (i.e. IPC) should be explored and could make an airborne component more feasible and would also provide additional benefits.
- The seeding generator array should provide good coverage for wind patterns ranging from southwesterly to northwesterly. Seeding sites east of the Wyoming Range are not recommended.
- Basic seeding criteria should be based on readily available (and quickly accessible) meteorological data, with more time consuming or less reliable data sources considered as secondary. Given the dearth of regular meteorological observations in the region, a program would benefit from deploying project-specific instrumentation (i.e. radiometer and soundings like what IPC operates out of Afton, WY). As such, program operators should coordinate with other entities in the region (i.e. IPC, Wind River Range program) regarding seeding decisions and to obtain beneficial observational and model guidance.
- If IPC is not engaged with their real-time modeling capability, it is recommended that a real-time modeling system be deployed over the region by the State of Wyoming to provide guidance on whether a storm is seedable by either ground or airborne seeding operations. This will save money by only operating when storms have high seeding potential, as well as can serve as a basis for seasonal program evaluation.

A rough estimate of April-July streamflow increases due to seeding indicated ~4,400–13,000 AF additional streamflow into the Green River Basin. A more robust hydrological study that utilizes a three-dimensional physical process-based hydrological model is needed to better estimate the benefits on streamflow.