

Executive Summary

**Evaluating the Precipitation and Streamflow
Impacts of Cloud Seeding in the Medicine Bow &
Sierra Madre Ranges**



prepared for
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by
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Precipitation and snowpack over the Medicine Bow and Sierra Madre Mountain Ranges directly affect water supply in the North Platte and Little Snake River Basins, thereby having far-reaching effects on agriculture/ranching, recreation, wildlife habitats, and the overall economy. Given wintertime precipitation is an essential quantity that provides necessary snowmelt during the spring and summer, agencies are becoming increasingly concerned with water supply as the changing climate becomes more evident.

With the goal of enhancing wintertime precipitation, the Wyoming Water Development Office (WWDO) has contracted with Weather Modification International (WMI) to conduct an aerial cloud seeding program focused on the Medicine Bow and Sierra Madre Ranges since 2018. In 2021, the State of Wyoming's Select Water Committee requested more information on quantifying the impacts of streamflow and an updated cost benefit analysis from the State's active and ongoing aerial cloud seeding program. In an effort to quantify the impacts of aerial cloud seeding on precipitation in the Medicine Bow and Sierra Madre target areas and assess the subsequent impacts on streamflow and water resources in the North Platte and Little Snake River basins, a numerical modeling capability (WRF-WxMod®) was coupled to a spatially-distributed hydrological model (WRF-Hydro®). Using this suite of advanced modeling tools along with flight-level cloud measurements and ground-based weather data collected during operations, an estimate of the additional streamflow in acre feet and associated cost effectiveness calculations, as well as scientific visualizations of the impacts of cloud seeding on precipitation and streamflow based upon the model simulations, are summarized in this report.

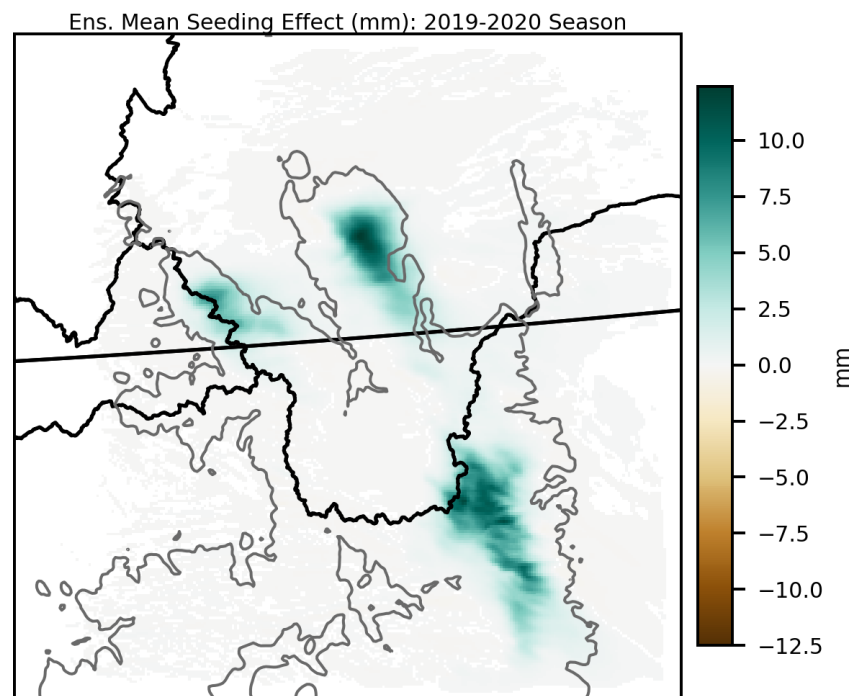
To ensure the work described in this report built on the knowledge and experience of past work, previous studies that have been carried out over the Sierra Madre and Medicine Bow ranges were reviewed and summarized, and a path forward focused on an ensemble-modeling approach incorporating observations when available.

The operational aerial cloud-seeding program targeting the Medicine Bow and Sierra Madre mountain ranges within the North Platte and Little Snake River Basins began in the fall of 2018. Therefore, when this study was commissioned, four complete winter seasons of aerial cloud seeding had been conducted and for which this evaluation study could examine (2018-2019, 2019-2020, 2020-2021, and 2021-2022). Given the need to first develop and test the ensemble-modeling methodology, this study proposed to evaluate one winter season with the allocated resources. Based on the availability of observations and taking into consideration the Mullen Fire impact during the 2020-2021 season, the 2019-2020 season was selected as the full season to simulate. Prior to simulating the entire season, two case studies were extensively simulated and analyzed as part of the methodology testing phase to ensure the ensemble design captured a range of solutions; one such case fortuitously displayed an unambiguous seeding signature observed by the Cheyenne NEXRAD weather radar.

WRF-WxMod was used to simulate airborne seeding cases from the 2019-2020 season using a nested domain set up that included a coarse, 3-km domain over the Western contiguous United States and a higher-resolution nested 1-km domain over the Sierra Madre and Medicine Bow Ranges, extending south into the Never Summer Range over Colorado. An ensemble design with a total of 36 members, including 12 control

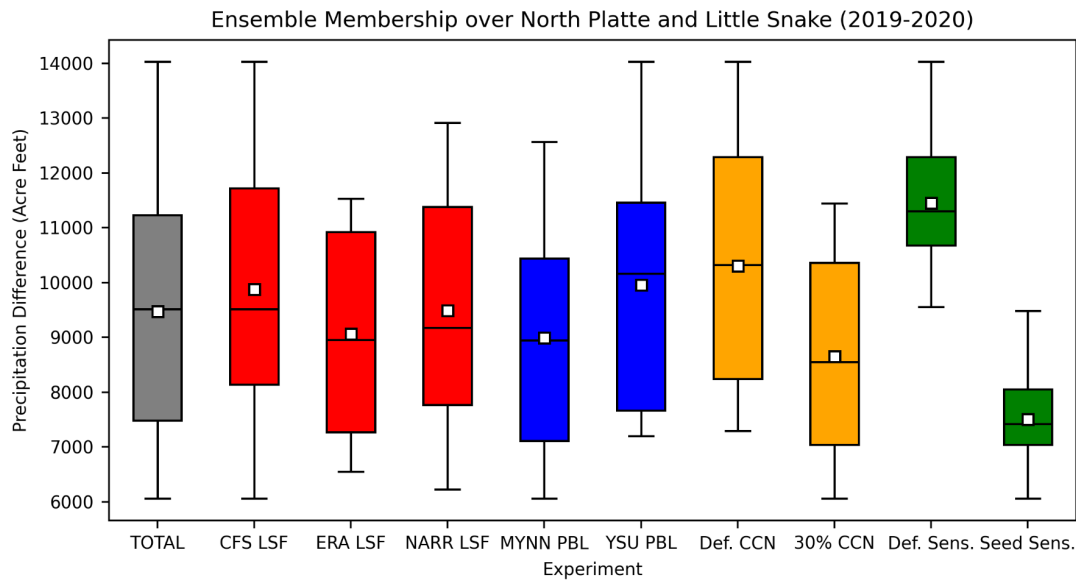
members (i.e., no seeding) and 24 seeded members, was run consisting of variations in large-scale forcing, planetary boundary layer schemes, background cloud condensation nuclei concentrations, and Silver Iodide activation rate and scavenging values (for the seeded runs only).

Overall, the ensemble mean of the total seasonal simulated seeding effect showed areas of increased precipitation over the highest elevations of the Medicine Bow, Sierra Madre, and Never Summer Ranges, which were the regions targeted by the operational aerial seeding program.



Total seeding effect (seed - control) for the ensemble mean over the 2019-2020 season. The black contour lines denote the North Platte and Little Snake River Basins. The gray contour lines denote where terrain is at 1500 and 2500 m.

In addition to investigating the simulated seeding effect using the ensemble mean, breaking down the seeding effect for each ensemble member provided a range of potential solutions. Across the primary area of interest, which includes the North Platte and Little Snake River basins, there was sensitivity in simulated seeding effects when using different large-scale forcing, planetary boundary layer schemes, background cloud condensation nuclei concentrations, and seeding activation and scavenging rate, with the largest changes coming from varying the seeding rates. For the North Platte and Little Snake River basins combined, the ensemble simulated seeding effect on precipitation for the 2019-2020 season ranged from a maximum of 14,030 acre feet (AF) to a minimum of 6,058 AF, with a mean value of 9,478 AF.

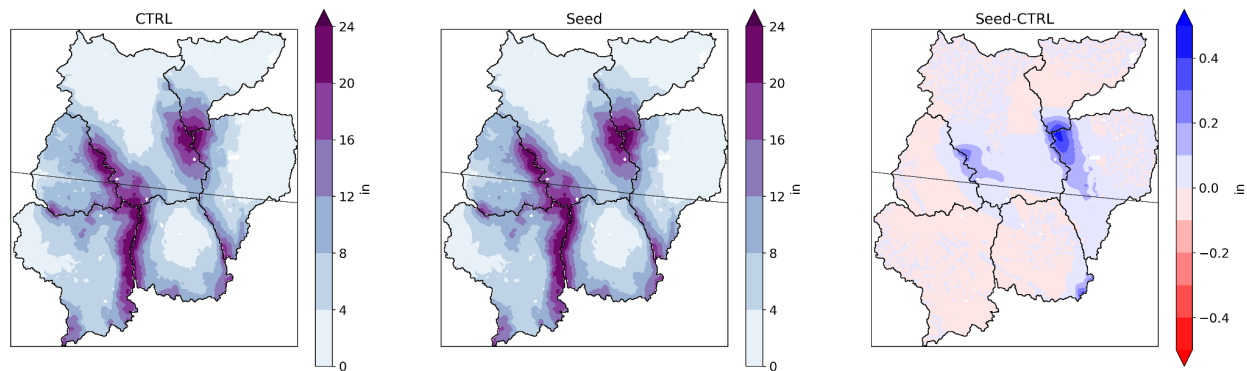


Box plots of seeding effect over the North Platte and Little Snake River Basins for the 2019-2020 season. The gray box includes all ensemble members; red boxes represent the subset of ensemble members with each large-scale forcing; blue boxes are the subsets with each planetary boundary layer scheme; orange boxes are the subsets with each cloud condensation nuclei concentration; green boxes are the subsets for each seeding sensitivity to Silver Iodide activation rate and scavenging values. The black line, or waist, of the box plot represents the median value, and the white square represents the mean value.

Using observations of liquid water content (LWC) measured by the seeding aircraft when it was available during the 2019-2020 season, it was found that median LWC values from all WRF-WxMod ensemble members were consistently lower than measured LWC values, indicating the model may have a low bias in LWC along the flight track (though LWC data was not available in all flights to confirm this was a consistent bias). Such a bias could indicate that the simulated seeding effects in the ensemble simulations may also be biased low. However, with limited atmospheric and LWC observations, further constraints, calibration, or quantification of the ensemble design and performance cannot be conducted. Nonetheless, the limited observations that were available seem well represented by the *spread* of the ensemble, and, therefore, there is confidence moving forward with interpreting that the seeding effect results lie somewhere within the estimated spread.

To assess the impacts of cloud seeding on streamflow, the WRF-Hydro model was first calibrated over the domain, and then baseline simulations were run from 1999–2021 to establish the long-term hydroclimate of the domain and provide a benchmark to compare against the seeding and non-seeding simulations. WRF-Hydro was run again to compare the effects of simulated cloud seeding on hydrologic responses from 1 October 2019 through 1 October 2020 inserting WRF-WxMod ensemble member simulation results of the seeding effect on the date that operational seeding occurred for all seeding cases during the 2019-2020 season for all 36 ensemble members. Dates during which seeding did not occur used a 4-km model dataset to force WRF-Hydro, so that the full water year precipitation accumulation was simulated. The control versus seeded hydrologic simulations were then compared in terms of snow water equivalent (SWE), evapotranspiration (ET), and seasonal flows across the domain.

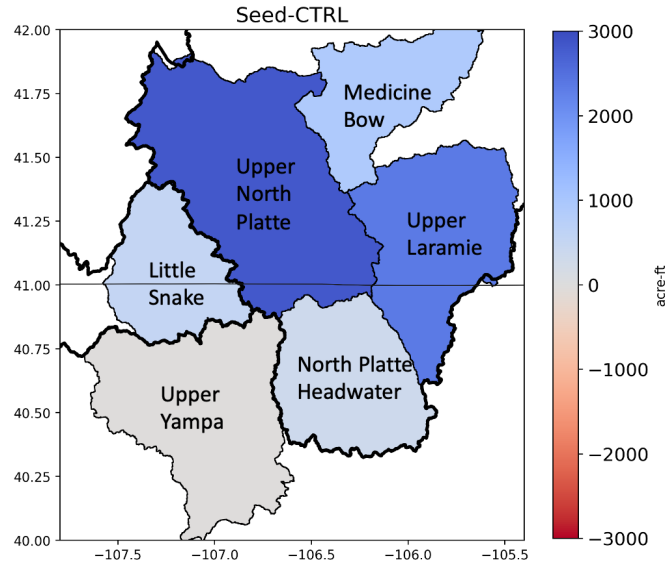
The peak SWE averaged over the control and seeded members showed similar pattern changes as the total precipitation, with the highest increase in SWE noted along the basin boundaries and higher terrain. Over all basins, total ensemble mean SWE increased by 8351 AF, with values varying from 598 AF (Little Snake) to 3903 AF (Upper Laramie) depending on the basin. While the seeded ensemble mean had slightly higher SWE values than the non-seeded (control) ensemble mean, the peak SWE date did not change between control-averaged and seeded-averaged simulations.



Peak SWE values for each basin in the domain, averaged over the control members (left), seeded members (middle), and their difference (right), where blue areas show increases and red areas show decrease. Black outlines show the HUC8 watershed boundaries.

To understand changes in the overall water budget for the 2020 water year during which seeding was simulated, the total accumulated evapotranspiration (ET) on 1 October 2020 was examined. Most basins showed small changes in ET due to simulated seeding, with an overall ensemble mean increase over all basins of 704 AF. The absolute change in ET values were less than changes in precipitation and SWE values, highlighting that the impact of seeding was largest on precipitation and accumulated snowpack. However, in the total water budget, both changes in precipitation and ET ultimately led to changes in streamflow.

In terms of streamflow, seeding simulations showed the largest impact on the Upper North Platte and Upper Laramie River basins, with an estimated ensemble mean increase in streamflow of 2828 AF and 2356 AF, respectively. Large increases in streamflow in those basins are consistent with seeding that targeted the Sierra Madre and Medicine Bow areas. Seeding simulations yielded a lesser impact on the Medicine Bow, North Platte Headwaters, and Little Snake River basins, with ensemble mean increases ranging from 348 AF to 892 AF.



The total ensemble mean accumulated streamflow (AF) difference between seeded and control simulations for each basin. Values in blue indicate an increase in streamflow, while pink values indicate a decrease. The thick black outline indicates the North Platte and Little Snake basin.

Over all basins in the model domain combined, ensemble mean simulations of seeding impact the water cycle by increasing precipitation by 8858 AF, increasing peak SWE by 8351 AF, increasing ET slightly by 704 AF, and increasing accumulated flow by 6921 AF.

The effects of simulated seeding on the water budget can be summarized by the ensemble mean seeding change in evapotranspiration, streamflow, and soil moisture divided by the precipitation change. For the water year 2020, the results show that for the total increase in ensemble mean precipitation, 78% goes to an increase in streamflow, 21% goes to an increase in soil moisture, and 8% goes to an increase in evapotranspiration. Note that these percentages do not add up to 100%, due to rounding and not accounting for the minor portion going to recharge groundwater storage in the model. Overall, the water budget analysis shows that increases in precipitation due to seeding largely increase streamflow, with secondary increases in soil moisture, and a slight increase in evapotranspiration.

Using the total operational costs provided by the state of Wyoming and its funding partners for the 2019-2020 aerial cloud seeding program, a cost-benefit analysis was conducted. Based on the range of the WRF-WxMod ensemble model output, costs for producing precipitation by cloud seeding range from \$40.52 - \$93.85/AF, with the ensemble mean at \$59.99/AF. For the WRF-Hydro ensemble model output, costs for producing streamflow by cloud seeding range from \$56.15 - \$124.22/AF, with the ensemble mean at \$81.87/AF.

	Precipitation Seeding Effect (AF)	Cost per AF (\$)	Streamflow Seeding Effect (AF)	Cost per AF (\$)
Ensemble Member Mean	9,478	\$59.99	6,945	\$81.87
Ensemble Range	6,058 - 14,030	\$40.52 - \$93.85	4,577 - 10,127	\$56.15 - \$124.22

WRF-WxMod and WRF-Hydro ensemble mean and range simulated seeding effect in acre feet (AF) and cost per AF over the 2019-2020 aerial seeding season over the combination of the North Platte and Little Snake River Basins.

Finally, recommendations for the future of Wyoming’s aerial cloud-seeding program consist of 1) suggested observational facilities that would aid evaluations and assessments, as well as improve operational efficiency, and 2) methods or approaches that could be employed to improve the operational efficiency and/or ensure the evaluation and ongoing assessments are following best practices. These are described in more detail below.

- 1) Future observational networks to advance hydrological assessments, aid evaluations and assessments, as well as improve operational efficiency, include:
 - A multi-channel radiometer would provide observations of supercooled liquid water path to aid in forecasting for operations, as well as in evaluation assessments.
 - High temporal resolution snow gauge network would provide on the ground measurements of snowfall, with a sub-hourly output frequency (ideally reporting every minute), to better detect impacts from seeding, whereas the existing SNOTEL network reports only hourly. These measurements would aid in evaluation and hydrological assessments.
 - Proximity atmospheric sounding(s) provide data on the vertical structure of the atmosphere, including the temperature of cloud layers, which aids forecasting for operations and evaluation studies.
 - A network of “gap-filling” X-band radars provide observations of clouds and precipitation in areas where the NEXRAD radar network is blocked by the mountains, which aid forecasting for operations, evaluation studies, as well as hydrological assessments. These data would also be valuable in sectors beyond the cloud seeding program, such as water resources management, fire and transportation weather stakeholders, mountain weather forecasting, etc.
 - Airborne lidar derived maps of snowpack conditions would aid hydrological assessments.
 - Trace chemistry measurements support evaluation studies of cloud seeding, especially pertaining to monitoring that environmental impacts of seeding with silver iodide continue to remain well below recommended levels.

The cost of deploying these networks will affect the cost-benefit analysis for an operational program, so it is also recommended that the costs of any observational facilities be considered when deciding which to deploy, and/or it is also recommended that cost sharing to install these capabilities with other sectors that would benefit from them (e.g., water resource management, transportation or fire weather sectors, weather forecasting organizations, etc.) be pursued to minimize the cost of the cloud seeding program.

- 2) Recommended methods or approaches that could be employed to improve the operational efficiency and/or ensure the evaluation and ongoing assessments are following best practices include:
- Conduct multi-year simulations of cloud seeding impacts to characterize the year-to-year variability in seeding impacts and efficacy
 - Consider simultaneous seeding of both the Sierra Madre and Medicine Bow Ranges when atmospheric conditions are favorable, by seeding upwind of the SM for potential effects across both mountain ranges
 - Use of ensemble model approaches and a multitude of observations to constrain uncertainties (see above for more details on recommended observations for evaluation studies).
 - Engage with the public and technical advisors through regular community meetings (this was demonstrated in the Wyoming Weather Modification Pilot Project with the Technical Advisory Team). These engagements help steer the program with subject matter expertise and community input to ensure the program meets the needs and addresses concerns of the community.
 - Explore a number of hydrologic model ensemble configurations, including different model physics, much in the same manner that ensemble configurations of the atmospheric processes impacting precipitation generation were implemented in the WRF atmospheric model.
 - Include water management modeling tools to simulate scenarios of runoff, storage, diversions, etc. to better understand the water use implications of precipitation and streamflow produced by cloud seeding.