CLOUD SEEDING AS A POTENTIAL WATER MANAGEMENT TOOL IN WESTERN SOUTH DAKOTA

Andrew G. Detwiler and Paul L. Smith
Atmospheric and Environmental Science Program and
Department of Physics
South Dakota School of Mines and Technology
Rapid City, SD 57701
Corresponding author email: Andrew.Detwiler@sdsmt.edu

ABSTRACT

Following several dry years in the late 1980's, cloud seeding was suggested as a potential tool for making more water available for use in the Black Hills region. Early estimates were that cloud seeding over the Pactola Reservoir watershed could produce 20,000-40,000 additional acre-ft of precipitation. Cloud seeding over the entire Black Hills was estimated to be capable of producing up to 10 times this much water equivalent on the ground. We refine several assumptions that were used in making these early estimates. Our primary refinement is that we use actual daily conditions during two winter seasons to assess whether seeding should be effective or not on that day, compared to the climatological weekly mean conditions used in previous work. We also refine the temperature threshold for effective cloud seeding. We arrive at significantly lower estimates for additional precipitation compared to the earlier ones. For the two winters studied, we estimated 3,000 to 7,500 acre-ft increase in precipitation into the Pactola catchment, and again 10 times this or more if seeding is conducted over the entire Black Hills region. Even though lower than the previous estimates, these new estimates are significant amounts of water in the context of the hydrological budget for the region. Both the earlier study and the study discussed here used several simplifying assumptions. Additional study using sophisticated numerical models of the atmosphere and its response to seeding is recommended to better define the potential impact of cloud seeding.

INTRODUCTION

Water management is an important consideration for economic and social development in semi-arid regions where total annual precipitation is less than 20" per year, such as western South Dakota. Typical sources of water in these regions include direct precipitation, surface water, and ground water. Management tools include reservoirs and canal systems to capture, store, and transport water. Indirect management tools include laws, regulations, and fees to control use of water for domestic, agricultural, industrial, navigation, and recreational purposes. In addition, users typically have a range of options for adapting their water usage to the available water, for instance, in the case of agriculture, by choice of crops planted. In the western United States, and several other semi-arid regions around the world, another practice sometimes adopted is cloud seeding to enhance natural precipitation.

The most common approach to cloud seeding is to disperse sub-micrometer particles of silver iodide from ground-based generators or from aircraft into clouds to accelerate the formation of precipitation. Less frequently, dry ice is dropped from aircraft into clouds in order to produce this acceleration. The conceptual model for cloud seeding is based on the reasoning that when precipitation development is accelerated, clouds start producing precipitation earlier and produce it more efficiently over a longer period, compared to natural (unseeded) clouds. The end result is more precipitation on the ground. In semi-arid regions, more precipitation on the ground can lead directly to increased crop yield, more water in storage in reservoirs for use for irrigation, municipal water supplies, hydroelectric power generation, and other beneficial uses. More precipitation also helps increase aquifer recharge.

In this preliminary study we summarize evidence to support the conceptual model for wintertime orographic precipitation enhancement by cloud seeding with an emphasis on results from recent studies that have provided strong support for this model. Then we summarize earlier work by Orville and Miller (1992) concerning the extent to which cloud seeding can be used to enhance wintertime precipitation over the Black Hills. We use the increased understanding of cloud seeding that has developed over the past two decades and examine daily weather records for a recent wet winter and a recent dry winter to re-evaluate the potential contributions of such cloud seeding to water resources in the Black Hills region.

How does precipitation form?—When water vapor condenses in saturated regions of the atmosphere to form clouds, microscopic water droplets are formed on micrometer and submicrometer dust particles called cloud condensation nuclei. These droplets grow by vapor deposition to sizes on the order of 20-30 micrometer diameter. Droplets in this size range have negligible fall speeds. In order for this condensed water to be precipitated from the cloud to the ground, the water must be aggregated into much larger drops or ice particles, of the order a millimeter or more in diameter. There are two main growth pathways from small cloud droplets to precipitation-size particles.

The first pathway is for liquid droplets of slightly different sizes having slightly different fall speeds to collide and coalescence. Initially this process is slow, because all the droplets are small and of similar sizes; consequently the differential fall speeds are also small. This process snowballs as the products of early collisions grow and fall faster, meaning they collide and coalesce with smaller droplets more quickly, and grow at faster rates. A few "lucky" droplets that get an early start and experience a rapid sequence of coalescence events can reach precipitation sizes while millions of vapor-grown droplets in the same region remain at small sizes still not having collided with another droplet. When there is a reasonably wide range of droplet sizes in a cloud region, this stochastic process can produce precipitation-size drops within tens of minutes of cloud formation. The wider the initial size range, the faster the development. This collision-coalescence process is described in more detail in many standard texts. Two recently published examples are Lamb and Verlinde (2011) and Wang (2013).

The second main growth pathway is for ice particles to fall into, or form directly within, a region of supercooled liquid droplets. Small droplets of the order of 20 micrometers in diameter can supercool and persist for many minutes without freezing, down to temperatures below -30 °C. In a cloud of supercooled liquid droplets, the droplets are in metastable equilibrium in a region that is saturated with respect to the liquid phase of water. If an ice particle forms near a supercooled droplet, the equilibrium water vapor pressure over the ice particle will be lower than that over the neighboring liquid droplet. The droplet will start to evaporate and the ice particle will grow. If there is a concentration of ice particles on the order of 1 per liter in a region where the cloud droplet concentration is on the order of 10^6 per liter (typical for a supercooled region in a young cumulus cloud), the water mass of a million droplets will evaporate in a matter of tens of seconds and deposit on the one ice particle, causing the ice particle to grow rapidly to precipitation size. This process is known by various names. We will call it the mixed-phase process. It also is commonly called the Bergeron-Findeisen process in honor of two scientists who, in the 1930's developed an understanding of how it works. Again, standard texts such as Lamb and Verlinde (2011) and Wang (2013) describe this process in greater detail.

How can cloud seeding increase precipitation?—The goal of cloud seeding is in essence accelerating the precipitation formation processes just described. By manipulating the aerosol particle population in the cloud region, the cloud seeder seeks either to (1) broaden the size spectrum of cloud droplets that condense initially in order to accelerate the collision and coalescence process, or (2) introduce ice particles into supercooled cloud regions to accelerate the mixed-phase process.

The first approach, broadening the cloud droplet size distribution, is addressed by introducing hygroscopic aerosol particles, typically particles composed of salts. Droplets relatively larger than those that condense on typical natural aerosols grow by condensing on these hygroscopic aerosols. This accelerates the collision and coalescence growth process.

The second approach, causing the formation of a low concentration of ice particles in a supercooled cloud region, is affected by introducing artificial aerosols that are good ice nucleators into a cloud, or by introducing very cold materials, such as dry ice pellets or liquid propane droplets, that accelerate the formation of ice particles in their vicinity. This approach is referred to as glaciogenic seeding.

There are two main processes for introducing these particles into clouds. First, small particles produced by combustion, vaporization, and condensation may be dispersed using propane-fueled burners from the ground fed with an acetone solution of silver iodide. This is relatively inexpensive. After release from a burner the particles are transported by winds and turbulent mixing up into the bases of clouds overhead.

Second, they may be dispersed from aircraft inside or in close proximity to the clouds. Wing-mounted burners consuming a solution of silver iodide in acetone can be used to produce the silver iodide aerosol. The aerosols can also be generated by burning pyrotechnic flares doped with silver iodide. Burners or flares fixed to an airplane circling under a cloud can release aerosol that gets carried upward and into the cloud by the convective circulations, or upstream of orographic clouds forming over mountains where airflow carries them into the clouds.

Finally, dry ice pellets can be dropped into supercooled cloud regions from above causing strong local cooling and enhanced formation of ice particles.

Airborne seeding methods are more costly and sometimes more hazardous to execute, but targeting can be more reliable, compared to use of burners on the ground. More detailed descriptions of both delivery methods, and variations and combinations of them, can be found in Dennis (1980) and ASCE (2006).

The Black Hills Situation—The meteorology and cloud physics of precipitation formation differs with season in the Black Hills region. Different cloud seeding approaches are needed in different seasons.

a. Winter—The winter season in the Black Hills region typically begins in October or November and lasts into April and sometimes May. The dominant precipitation type at the ground in winter is snow, although rain can occur in any month and can dominate in the earliest and latest months of the season. Precipitation most often is produced by synoptic-scale surface low pressure systems that track northeastward out of Colorado across the High Plains, and also by low pressure systems tracking southeastward out of the Alberta region and passing across the northern Black Hills. Counterclockwise circulation around the Colorado Lows as they pass to the east of the region results in upslope flow along the eastern flank of the Hills. Counter clockwise circulation around the Alberta Lows (also called Alberta Clippers) impinges on the Hills from the north and west. In both cases, moist air near the ground rises and cools as it flows toward and over the Hills, producing clouds due to this orographic lifting induced by the generally NNW-SSE oriented Hills. Precipitation generally results if the moist layer is deep enough and upslope flow is strong enough. Maximum amounts typically fall on the windward flanks of the Hills. Orographic forcing is the major component of the forcing that produces these clouds, but convective processes can also contribute.

These clouds are cold, and snow develops by the mixed-phase process. Glaciogenic seeding is appropriate for enhancing precipitation from these clouds. It can be used to initiate precipitation sooner and extend it for a longer period as the storms pass near and over the Hills. Glaciogenic seeding can also be effective for enhancing precipitation from orographic systems with embedded convective elements. For summaries of results from orographic seeding projects, see reviews in Dennis (1980, Section 7.4), Bruintjes (1999), National Research Council (2003), and Silverman (2010). Although these summaries generally support the efficacy of orographic cloud seeding, they highlight several uncertainties. The main two concerns are the variable statistical support for increases in precipitation from different projects, and weak demonstration of physical links between the release of seeding material and increased precipitation on the ground.

Two recently-completed orographic seeding experiments, using observations from more advanced and more comprehensive systems of instruments than have been used in the past show very encouraging results and address concerns expressed in the earlier reviews cited above. The first was the Snowy Mountain project (Manton et al. 2011), conducted from 2005-2009 in the Snowy Mountain region of southeastern Australia. The Snowy Mountain project was designed to evaluate the effect of cloud seeding on precipitation in a region closely similar to the Black Hills in topography and climate. It included much improved monitoring of movement and effectiveness of seeding materials after release, and more complete precipitation measurements compared to earlier studies. Randomized seeding was conducted in 5-hr experimental units when conditions were appropriate for seeding. Two-thirds of these units were seeded and one-third unseeded. Manton et al. (2011) and Manton and Warren (2011) suggest precipitation increases during seeded experimental units of 14% with observations to support a clear physical link between the seeding and the precipitation increase.

The other project was the Wyoming Weather Modification Pilot Project (WWMPP) conducted in Wyoming from 2007-2014. The main focus of the WWMPP was wintertime snowfall in the Sierra Madre and Medicine Bow mountain ranges, although some work was also done in the Wind River Range. Although close to the Black Hills, these mountain ranges are taller than the Black Hills and snow falling on them originates higher in the atmosphere where conditions are colder. Breed et al. (2013) describe the evaluation procedure used to assess results from the project. As in Manton et al (2011), the Wyoming experiment identified limited-duration experimental units (of 4 hrs length in this project) when conditions were conducive to precipitation enhancement by seeding, and compared precipitation from seeded units and unseeded units. Extensive meteorological measurements, as well as monitoring of the transport of seeding material, were conducted. Although the project was just completed in 2014 and formal publication of results has not yet occurred, a draft executive summary of results from the project was released in December 2014. It is available from the Wyoming Water Development Commission at http://wwdc.state.wy.us/weathermod/WYWeatherModPilotProgramExecSummary.pdf.

Preliminary results from the WWMPP were not as strong statistically as for the Snowy Mountain project, but the best estimate of the percent precipitation enhancement is in the range 3-17% for events in which seeding material was most effectively targeted. Detailed process studies show clear links between the generation and dispersal of seeding aerosol and enhanced precipitation.

b. Summer—In summer, when a moist near-surface boundary layer is heated as it passes over sunlit terrain, warm moist air currents rise above the surface. If the air above the boundary layer is sufficiently cool, then these rising currents accelerate and thunderstorms form. Typical Black Hills region thunderstorms are warm in their lower portions and cold in their upper portions. Experiments have been done on convective clouds in the region using hygroscopic seeding techniques to enhance precipitation produced by the collision and coalescence process in the lower warmer regions, and glaciogenic seeding techniques to enhance precipitation produced in the upper mixed-phase regions of convective clouds. Conversion from supercooled liquid to ice in the upper regions of these storms, caused by introduction of ice nuclei, can release additional latent heat of fusion (the so-called dynamic seeding effect) earlier in the storm lifetime, and can invigorate the convection and lead to additional precipitation compared to unseeded storms due to the cloud being more vigorous and longer lasting. Experiments using both glaciogenic and hygroscopic seeding were conducted in the Black Hills region from the 1960's into the early 1970's with mixed results. (See, e.g., Dennis et al. 1975).

Development of precipitation in summer convective storms is much less predictable than in winter storms because it depends more on unpredictable small-scale variations and interactions in cloud circulations and cloud microphysical characteristics, and on chance interactions between the circulations of neighboring storms. Because natural precipitation from summer convective storms is quite variable, the impact of cloud seeding on precipitation can be difficult to separate from the natural variability between storms. It is therefore more difficult to discern the impact of cloud seeding on summer convective storms than for winter storms. Further, even though there have been experimental programs demonstrating precipitation increases from seeding of convective clouds, the physical chain-of-events connecting the seeding to the precipitation increase is not well understood. See reviews in Dennis (1980, Section 7.5); Bruintjes (1999); Silverman (2001); National Research Council (2003); and Silverman (2003) for further discussion of the issues. This reduces confidence in the predictable use of cloud seeding to enhance precipitation from summer convective clouds.

For purposes of this study, we will not include the potential impact of summertime seeding on summer rainfall. We will focus on wintertime seeding for which there is stronger scientific support.

What could be the impact of cloud seeding on wintertime precipitation in the Black Hills region?—Results summarized in the reviews cited above, as well as recent results from the Snowy Mountain project and WWMPP, lead to the expectation that seeding of wintertime orographic cloud systems can lead to increases in precipitation from those systems on the order of 5-15%. This range is incorporated into the Weather Modification Association's Capabilities Statement on Weather Modification, adopted September, 2011, available at http://www.weathermodification.org/capabilities.php#Winter. This percentage range is based on analyses of the results of a large number of experimental and operational winter seeding programs in a variety of regions. Precise results are in general dependent on specific meteorological and topographical characteristics of the region, along with specific procedures followed and seeding materials used in particular projects. It cannot be assumed that this range of increases is likely in all orographic seeding situations.

Orville and Miller (1992) were the first to publish a study on the potential for cloud seeding to enhance winter precipitation over the Black Hills. Hereafter we will refer to this work as OM. This preliminary study was done in response to Black Hills region water shortages that occurred during a series of relatively dry years spanning the late 1980's to 1990. Their approach was very simple: They assumed wintertime precipitation was predominantly orographic and assumed total winter precipitation could be increased by 10% by cloud seeding. They estimated the months of the year during which glaciogenic seeding was feasible based on climatological average temperatures at the highest elevation of the Black Hills, took the climatological average precipitation occurring in those months, and assumed an additional 10% of this could be coaxed from wintertime clouds over the Black Hills by seeding. They focused their attention on precipitation into the Pactola Reservoir watershed, the main reservoir on Rapid Creek. Their main conclusions are:

- Glaciogenic cloud seeding over the Black Hills in winter could lead to 20,000-40,000 acre-feet of additional precipitation into the Pactola/Deerfield watershed in the central Black Hills. If 22.5% of this runs off into the reservoir, the additional water to be stored is 4500 – 9,000 acre-ft. [Compare this precipitation to the average annual inflow into the Pactola Reservoir, which is 35,000 acre-ft.] This is a potentially significant addition.
- From November through May mean temperatures near the highest elevations in the Black Hills indicate glaciogenic seeding is possible. There are on average 50-70 days with precipitation. They assumed that conditions over the Black Hills were suitable for precipitation enhancement by seeding on all of these days during these months.
- Seeding over the Black Hills is unlikely to diminish precipitation over regions downwind of the Hills.
- Seeding will be most effective if a combination of ground burners and airborne dispersion of seeding materials is used.
- The expected cost (in 1992 dollars) of conducting seeding operations over the entire Black Hills would be on the order of $250,000/year. Scientific analysis of meteorological and hydrological data to assess the effectiveness of the seeding would cost about the same, leading to a total of $500,000/year to conduct seeding and monitor its effects.
- A study should cover at least 5 years for the experiments to span a range of meteorological regimes and for a large enough number of events to occur for a 10% increase in precipitation to be detected.
- Periodic, intensive, special scientific studies to pursue better understanding of the detailed physical processes by which cloud seeding enhances precipitation (similar to what actually happened during the Snowy Mountain and WWMPP projects described above) could add another $500,000 in costs during the years they are conducted.

In the present study, we revisit this topic after a quarter century of additional studies of cloud seeding since OM. We present new analyses of the potential for precipitation enhancement, apply insights gained in the Snowy Mountain and WWMPP projects, and update the conclusions of OM.

METHODS

Estimate frequency of opportunities for glaciogenic cloud seeding in the Black Hills region—In their earlier work, OM looked at the number of days per winter with precipitation events at all reporting stations in the Black Hills. The numbers ranged from the upper 50's to the low 70's in the southern Black Hills to the low 100's at Lead and Hardy Ranger Station in the higher elevations of the northern Black Hills.

Artificial ice nuclei will only nucleate ice particles at in-cloud temperatures significantly below 0 °C. Based on climatological weekly mean temperature at the 700 hPa level (corresponding to 3.0 km altitude above mean sea level, and roughly 1 km above the highest elevations in the Black Hills from the Rapid City radiosonde record being -5 °C or lower, OM deduced that precipitation should be forming by the mixed-phase process and conditions should be suitable for seeding for all precipitation events from October through May. They assumed that all precipitation falling during the months November through May, accounting for roughly 50% of total annual precipitation, could be enhanced by seeding. Although it is not clear from OM, in Orville (1992), it is apparent that the impact of seeding on precipitation is taken to be a 10% +/- 3.3% increase in total precipitation during this period. In this way they arrive at an increase of precipitation into the Pactola Reservoir drainage basin of 20,000-40,000 acre-ft. Of this increase, OM estimate 15-30% will run off and collect in the reservoir. If we take the OM mean estimated precipitation increase of 30,000 acre-ft and a mean estimate of 22.5% run-off, this amounts to 6,750 additional acre-ft of water added to the reservoir each winter season.

If seeding were conducted over the entire Black Hills region (covering approximately 15,000 km^2), the corresponding estimated increase in water equivalent of winter precipitation is 10% of half of an estimated 6,000,000 acre-ft falling over the entire Black Hills region annually, or 300,000 acre-ft. of water. If 22.5% runs off, there would be an extra 67,500 acre-ft ending up in Black Hills streams and surface reservoirs. A roughly similar amount would recharge the important aquifers exposed in different locations in the Hills, and the rest will evaporate or be transpired through plants back into the atmosphere.

A look at two daily seeding scenarios—OM recommends that these estimates can be refined by looking at daily temperature and precipitation data. Their assumption that all precipitation events from October – May are orographic and seedable is an optimistic first order approximation. In response to this recommendation, we looked at daily precipitation data for two stations in the central Black Hills, Pactola Dam and Custer, along with the vertical temperature profiles from the Rapid City sounding during precipitation events.

Daxiong and Finnegan (1989) show that a high percentage of artificial nucleating particles generated using current technology really only become active at temperatures of -10 °C and below. For each day with snow and a liquid equivalent precipitation amount recorded, we assume that precipitation could have been enhanced by seeding if the temperature at 700 hPa (within 1 km above the highest elevations of the Black Hills) was -10 °C or lower sometime during the precipitation event on that day. This is a lower (colder) temperature threshold than the -5 °C utilized by OM and can be expected to reduce the estimate of how frequently cloud seeding can be carried out. At the level of the approximations we are using, however, we believe it is more realistic based on studies of nucleation of silver iodide aerosol particles.

For purposes of our study, we assume that ice nuclei will be dispersed from ground generators placed on the upwind flanks of the Black Hills. Such seeding aerosol releases will normally not reach regions higher than 1 km above the highest elevations in the Black Hills, if that far, in the absence of embedded convection. OM suggest that airborne seeding could be used to reach higher, colder altitudes in clouds, if the clouds extend upward that far. However, in another work, Orville (1992) notes the increased expenses and physical difficulties of airborne dispersal of ice nucleants in orographic clouds in winter storm conditions. We assume that economics and safety concerns will likely dictate the use of ground seeding only.

Finally, we did a day-by-day analysis of whether or not cloud seeding can be expected to enhance precipitation, rather than use weekly and monthly mean conditions. Winter weather can be quite variable in the Black Hills region and we attempted to capture that variability with this approach. We chose two sites in the central Black Hills with good precipitation records, Custer and Pactola Dam, and looked at daily precipitation amounts for two winter seasons, along with temperature and dew point profiles between the ground and the 700 hPa level on the Rapid City radiosonde. Details are given below.

Figure 1 shows monthly precipitation over the entire Black Hills region from January, 2011 through March, 2015. It can be seen that winter 2011-2012 was the driest winter during the period, while winter 2012-2013 was wetter, particularly the later winter months of March – May in 2013. We analyzed these two winters as representative of a typical range of weather conditions in the Black Hills region. Although this may not perfectly represent the long-term area climatology, it is a refinement over the OM assumption

Atmospheric soundings from the Rapid City National Weather Service office are available at 0000 or 1200 Universal Time (1700 local standard time the previous day, and 0500 local standard time of the current day). We assume these are representative of conditions over the Black Hills. If temperature anywhere between the ground and the 700 hPa level was -10 °C or below, and dewpoint was within a few degrees of the air temperature over some portion of this layer, we considered the day seedable. Even if these conditions were met, but surface temperatures were above 10 °C (50 °F) at both sounding times, then the day was considered unseedable. We also reviewed the national surface weather composite weather map available from UNISYS (http://weather.unisys.com) for a general characterization of synoptic-scale weather conditions in the region on days with precipitation.

OM applied an enhancement percentage to the total precipitation falling from November through May. However, for purposes of this study, we will assume an average 10% increase in precipitation on days when precipitation was observed and the day was seedable according to the above criteria. In other words, we assume seeding can increase precipitation only on days when it is cold enough and cloud conditions are suitable. Our criterion for "cold enough" is admittedly crude, but the concept that seeding may be feasible on some days and not others during the winter season is a refinement compared to the study of OM.

Data sources were:

- National Centers for Environmental Information (formerly the National Climatic Data Center) for daily precipitation. Observations of 24 hr precipitation amounts were recorded near the start of the work day at the Pactola

Dam at 0800 local time, and at 1300 local time at the U.S. Forest Service office in Custer.

- University of Wyoming weather web site, http://weather.uwyo.edu , for the Rapid City radiosonde sounding records.
- UNISYS weather web site, http://weather.unisys.com , for national surface weather composite charts valid at 0000 and 1200 Universal Time.

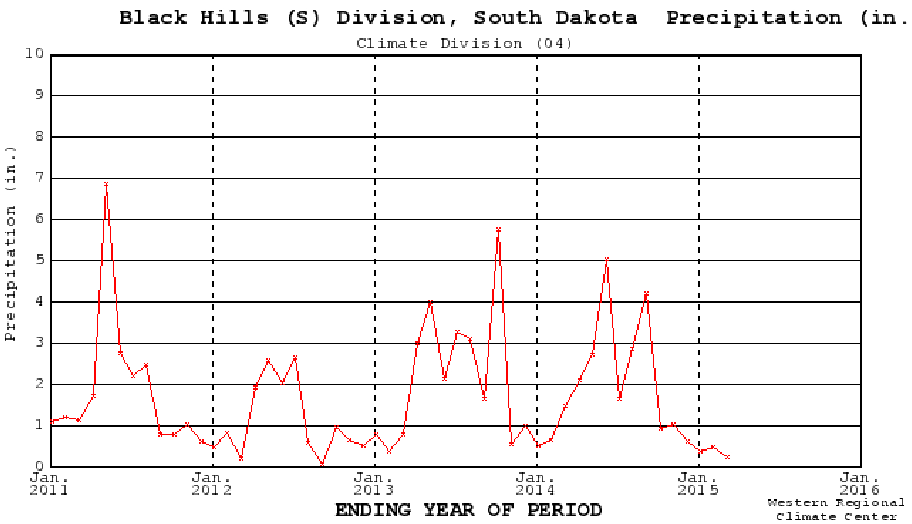

Figure 1. Monthly precipitation over the Black Hills climate division from January 2011 to March 2015. Source: Western Regional Climate Center.

RESULTS

A map of the Black Hills region with topographic contours and with the locations of the observing sites depicted is shown in Figure 2. Although on days with substantial precipitation both stations usually reported precipitation, on days with light precipitation sometimes only one of the two stations reported precipitation. On occasion, data were flagged as missing. In addition, it is clear from comparing the records at the two sites, and reviewing the composite surface charts, that reports on some days at one or the other station represented precipitation for the current period and one or more prior ones. This was more likely to occur over weekends than on weekdays. This introduces some uncertainty into our analysis, but we do our best to minimize the impact on our results

In Table 1 we compare the precipitation during what we will call the winter period (October – May) to precipitation during the entire water year (October – September). It can be seen that annual and seasonal precipitation amounts at the two sites are similar, with Pactola having slightly lower total water year precipitation in both seasons. The water year precipitation totals were 20 to 30% higher

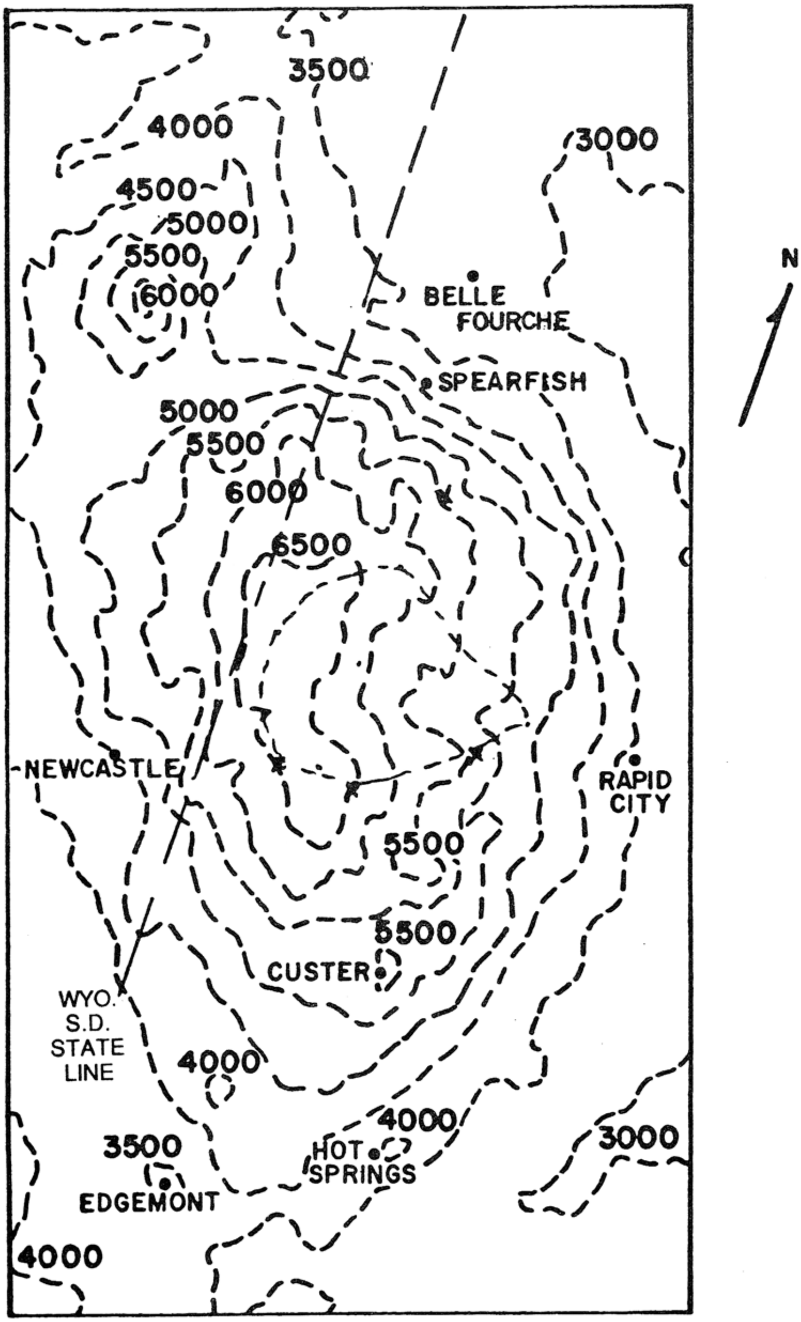

Figure 2. Topographic map of the Black Hills region with bold dashed isoheights indicating elevations in feet. The location of Custer is labeled and the outline of the Pactola Reservoir drainage basin is indicated by a light dashed line with the dam at the east end of the outline. Source: Orville (1989).

in 2012-2013 compared to 2011-2012. Winter (October – May) precipitation represents roughly half of the water year total precipitation at both sites in both water years.

Table 1. Water Year (Oct-Sept) and Winter (Oct-May) precipitation in inches at Custer and Pactola Dam for the seasons 2011-2012 and 2012-2013.

	2011-2012 Water Year	2011-2012 Winter	2012-2013 Water Year	2012-2013 Winter
Custer	14.06	7.08	16.64	8.48
Pactola	12.23	7.31	15.65	8.07

The results of analyzing the situation for seedable days, as described above, are shown in Table 2. Total days in the season with precipitation were added up as days with precipitation at either Custer or Pactola. Seedable days were days with precipitation and temperature conditions at either Custer or Pactola suitable for seeding. The seasonal precipitation, October- May, is the average of the seasonal precipitation at the two sites. (See Table 1.) The observed precipitation on days suitable for seeding is the average of this quantity for the two sites for 2011-2012, and the precipitation at Pactola only for 2012-2013. In 2012-2013 precipitation observations at Custer were missing for most of the month of January, while there were 11 days that month with precipitation at Pactola. Although the missing data probably did not have a big effect on water year totals (Table 1), it had a significant impact on the number of seedable days and total precipitation on all seedable days. So for 2012-2013 we use Pactola data to represent seedable days.

Table 2. Analysis of precipitation on seedable days in winter (October – May).

	Precipitation Days	Seedable days	Seasonal precipitation (in.)	Precipitation on seedable days (in.)
2011-2012	78	30	7.20	1.90
2012-2013	90	64	8.28	4.61

Table 2 shows the two winter seasons to be very different. There were twice as many seedable days in 2012-2013, and more than twice as much total precipitation on seedable days, compared to 2011-2012. As weather varies from season to season, the results from seeding will also vary. Precipitation on seedable days was 26% of total winter precipitation for 2011-2012, while it was 56% of total winter precipitation for 2012-2013.

There were no seedable days in October, 2011, and only one in October, 2012. There were no seedable days in April, 2011, but 10 in April, 2013. There were no seedable days at all in either May, 2012, or May, 2013. Almost all seedable days occurred during the months November to April.

We *assume* a 10% increase in precipitation can be produced on seedable days, and use the precipitation amounts on seedable days as representative of precipitation falling into the Pactola Dam catchment. If we assume a catchment area of 800 km^2 (OM), then we can convert this precipitation into acre-ft of additional water falling into the catchment. If we assume 22.5% of this additional precipitation ends up in the reservoir, we can estimate the contribution of seeding to water stored in the reservoir, following the same line of reasoning as OM. Results of this calculation are shown in Table 3. These results mirror the distinct differences between the two winters seen in the precipitation and seedable day statistics shown in Table 2. Using the assumptions made in this study, we estimated the additional storage due to enhanced precipitation produced by seeding to be less than 1000 acre-ft for winter 2011-2012, and not quite 2000 acre-ft for 2012 -2013.

Table 3. Estimates of seeding effects on precipitation (P) and storage at Pactola.

Winter	P (in.)	P (acre-ft)	Storage (acre-ft)
2011-2012	0.19	3130	704
2012-2013	0.461	7594	1709

These estimates are the product of very simple assumptions about the characteristics of days on which seeding can be effective, and the precipitation increase resulting from seeding. Evaluating whether seeding can increase precipitation on a daily basis, and using a lower temperature criterion for effective seeding, have produced dramatically lower estimates of the impact of seeding compared to those of OM. Both estimates of increased winter precipitation into the watershed, roughly 3000 acre-ft for 2011-2012 and roughly 7500 acre-ft for 2012-2013, are far below the estimates of Orville and Miller (1992) of an additional 20,000-40,000 acre-ft over an average winter.

If seeding is conducted over the entire Black Hills region, estimating the potential increase in precipitation to the ground is more challenging. The northern Black Hills on average receive more winter precipitation, and have a higher number of days per winter with precipitation, compared to the central and southern Black Hills regions (Orville and Miller 1992). If we assume the statistics derived above based on precipitation at Custer and Pactola are somewhere near an average between the northern and southern Black Hills region, and apply the precipitation increases in Table 3 to the entire region, covering roughly 15,000 km^2, then the additional precipitation on the entire region would be 59,000 acre-ft in a winter with the characteristics of 2011-2012, and 142,000 acre-ft for a winter like 2012-2013. This water would be an additional contribution to the regional water budget. Some would end up in one or more of the several smaller reservoirs around the Black Hills, but most of it would be much less manageable than the water falling into the Pactola basin.

SUMMARY AND CONCLUSIONS

This study seeks to further evaluate the potential utility of cloud seeding as a water management tool in the Black Hills region by refining earlier work by Orville and Miller (1992). A review of the literature on cloud seeding suggests that for this region wintertime seeding is likely to produce consistent precipitation increases; the impact of summertime seeding is not as certain. We extend the earlier work by considering seedability of storms on a daily basis and re-evaluate estimates of the quantity of additional precipitation that might be produced by a wintertime cloud seeding program. We use daily weather records for a dry winter and a wet winter. In addition, we assume precipitation enhancement requires lower temperatures than were assumed in the earlier study. By estimating precipitation enhancement on a daily basis, we arrive at a lower but still significant precipitation enhancement compared to Orville and Miller (1992). By our estimates, cloud seeding could contribute from one to several thousand additional acre-ft per winter to water stored in the Pactola reservoir in a typical winter. This is to be compared to the average annual inflow to the reservoir of 35,000 acre-ft. If clouds over the entire Black Hills region are seeded, when conditions are conducive to precipitation increase, in the neighborhood of 100,000 acre-ft can be added to the water budget of the Black Hills region. In all but already very wet years, this addition would be beneficial. Orville and Miller (1992) estimate that the incremental increase in cost to seed over the entire Black Hills regions compared to seeding just over the Pactola catchment is just 25%. For future studies, it would be best to plan on seeding over the entire region in order to get maximum return on investment in the form of additional water on the ground from the seeding.

Although it would be possible to proceed at this point to a multi-year physical study, like the Snowy Mountain or WWMPP studies, another option at this stage of consideration is performing numerical simulations of several seasons of weather, with parameterization of dispersal of seeding material and its impact on precipitation included in the simulation along with the normal natural meteorological processes. Cotton et al. (2006), Saleeby et al. (2007), Xue et al. (2013a) and Xue et al. (2013b) have recently demonstrated that current numerical weather prediction models are sufficiently sophisticated to incorporate a seeding mechanism and produce results from seeding in reasonable agreement with observations. It would be possible to numerically simulate several winter seasons over the Black Hills and compare results with and without seeding, for less than the cost of one year of a physical seeding study. It would be useful to have insights from these numerical studies to help refine the design of an experimental or operational seeding project.

Before seeding operations are implemented, consideration also needs to be given to socio-economic impacts of seeding. Orville and Miller (1992) discussed some of these issues, such as impact on driving conditions, wildlife, and the ski industry. We defer further discussion of these issues to a subsequent publication.

Overall, we find the potential benefits of cloud seeding over the Black Hills to be significant and advocate for continued discussion and study of how best to achieve them.

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