"REVIEWED"

A REPORT ON THE CONFERENCE ON THE SCIENCE AND TECHNOLOGY OF CLOUD SEEDING IN THE BLACK HILLS

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The past few years have seen a diminishing water supply in the Black Hills of western South Dakota and eastern Wyoming. Water levels in the reservoirs in the region have decreased to less than 50% of capacity, some as low as 10%. This causes great concern about future agricultural and municipal water supplies in the area, particularly in light of the fact that the Black Hills are a water resource for an area much more extensive than the Hills themselves. Plans are underway by various groups to drill wells, repair irrigation ditches, improve conservation methods, and study and define more precisely the surface and ground water characteristics of the Hills.

In recognition of these problems, a conference was held in Rapid City at the South Dakota School of Mines and Technology on October 16-17, 1989, designed to highlight the water problem, discuss the status of cloud seeding to help alleviate the problem, review what has been accomplished by cloud seeding in the region in the past, and outline the main steps in pursuing an operational and research project in the region. Many experts in the field were invited to give presentations. The conference was open to the public and various municipal, state, and industrial officials were invited to the sessions. The City of Rapid City, Pennington County, West Dakota Water Development District, South Dakota School of Mines and Technology, and the Institute of Atmospheric Sciences (IAS) co-sponsored the conference.

Mayor Keith Carlyle of Rapid City opened the conference and related some of his experiences over the past couple of years as the realization of the impacts of the drought deepened. He noted that four out of the last five years have been drought years in this area. He had asked for water restrictions in 1988, but that was not approved by the Common Council. A Drought Committee, under the Chairmanship of Dr. R. A. Schleusener, was formed in the beginning of 1989 and has helped him educate the community and decide upon appropriate actions to take.

In 1988-89, 6,000 acre-feet of water have been conserved by methods taken by the City; this translates to about 12 feet of capacity in the Pactola Reservoir. Recreation is at least a $21 million industry in the Black Hills and is suffering from the low level of the reservoir. Several things besides conservation are being done to help. A forest thinning program is being considered, which has a potential for increasing runoff by possibly 32% (to about 11% in the Pactola watershed).

Next, a bit of the history and setting for this particular conference was given by Harold Orville. The winter of 1988-89 and the spring of 1989 had been a time in which articles in the Rapid City Journal and memos from Orville to several groups had drummed up interest with regard to weather modification as a potential aid in alleviating the drought. A white paper was prepared concerning the cloud seeding potential of the Black Hills and is available to anyone interested as Bulletin 89-3 from the Institute of Atmospheric Sciences (IAS). The citizens of Rapid City and Pennington County, through the West Dakota Water Development District, contributed enough money to fund a small pilot project which ran from 22 April to 15 June and was reported on later in the conference.

The conference was organized to satisfy the following objectives:

1. Provide information to the public (over 400 man-years of scientific experience was available from the personnel at the conference).

2. Identify and discuss critical issues.

3. Make decisions about future activities.

4. Form an organization (or identify an existing one) to take the actions decided upon, if any.

In this introductory presentation, several concerns were discussed, such as: 1) could a flood be caused (which harkens back to the 1972 Rapid City flood); 2) will the water still be available for others, if additional water is precipitated on the Black Hills; and 3) what will the cost of such a project be. Most of these issues were treated by speakers during the conference.

The Black Hills topography was shown and the principal reservoirs pointed out. The Black Hills provide good uplift of moist air for winds from most any direction, but the greatest uplift comes with winds from the southeast. The general motion of the weather systems is from the west, but low-level flow brings moisture in from the south or southeast most often. The dynamics of the clouds are enhanced over the mountains, leading to extra precipitation there (nearly double the amount of precipitation found 50 to 100 miles east of the mountains). The clouds weaken as they move off the Hills and then produce less precipitation. This is often referred to as a rain shadow effect.

Papers having to do with defining the problem were presented during Session 1, which Dr. Paul Smith of the IAS chaired. Mr. James Miller of the IAS described the climatology of the Black Hills. He showed a tree ring index representative of the

Black Hills which indicated a few periods in the past in which droughts were more severe and longer lasting than the present situation. Average precipitation over the Black Hills is approximately 21.3 inches, with 1989 coming in at a little below average. Greater amounts occur in the northern Hills, less in the southern Hills. Most of the 1980's have been below average in the Black Hills' division stations. Mr. Miller also showed the normal precipitation by month, indicating a maximum in June and an average of about 11 inches of precipitation from November through the end of May (one period of potential cloud seeding). The amount of precipitable water in the atmosphere maximizes in July. The 24-hour probability of precipitation shows about a 20% chance in the winter months, increasing to 30% in the spring and approaching 50% in June. This indicates that the number of days of precipitation in a month ranges from about 6 days in the winter months to slightly less than 15 days in June.

At the surface, the winds were shown to be primarily from the west through northwest with a secondary maximum from the southeast at the surface in the winter and spring. At 700 mb (about 10,000 ft), the winds are primarily from the southwest to the northwest; these are the directions from which cloud seeding would probably be done most frequently.

Mark Anderson of the USGS spoke on the hydrology of the Black Hills. He mentioned that precipitation had been below the mean for the last five years, and that the last three years have been more than one standard deviation below the mean. He indicated that the Cheyenne River flows at about 94 cubic feet per second (that is, about 190 acre-feet a day) at Edgemont in the southern Hills, and 320 cubic feet per second at Wasta to the east of the Hills. This shows the influence of the Black Hills in adding water to the surface water supplies. The Cheyenne River above Edgemont is fed by an average of 13 gallons per day per acre in the watershed. The Belle Fourche River west of the state line yields 27; Rapid Creek, 150; and Spearfish Creek, 312 gallons per day per acre. The runoff efficiencies (ratio of runoff to precipitation in the various watersheds) are for the Sturgis watershed, about 27%; Spearfish Creek, 22%; Rapid Creek above Pactola, 8.3%; and the Powder River Basin in Wyoming, 5.3%. Fall River runoff in the 1940's averaged 29 cubic feet per second and in the 1970's and 1980's has averaged only 21.5 cubic feet per second, a significant drop.

Mr. Anderson emphasized that the Black Hills and its precipitation are a resource to an area which is very large compared to the Black Hills. All of western South Dakota and some of eastern Wyoming are served by the Black Hills. The Madison aquifer covers a five-state area; the main input is from the Black Hills and the Big Horn Mountains. The Rapid Creek loss to the Madison aquifer averages about 8 cubic feet per second, but increases up to 14 cubic feet per second in dry years. A well near Reptile Gardens south of Rapid City has dropped approximately 20 feet since the beginning of 1988, and a total of 50 feet since mid-1987.

Bruce Laymon of the U.S. Bureau of Reclamation in Newell reported on the storage of Deerfield and Pactola Reservoirs. Deerfield was built in 1949 and Pactola in 1956. Pactola Dam was filled in 1962 and stayed nearly full until 1987. The two reservoirs are a pooled storage operation with Deerfield having about 15,000 acre-feet and Pactola about a 55,000 acre-feet capacity. Pactola was down about 8 feet in 1987, 27 feet in 1988, and more than 45 feet in 1989. The net inflow over the last three years has been about two-thirds of the 30-year normal. The inflow in July and August of 1989 was 14% of normal. The 1989 usage has actually been less than in 1988: 10,000 acre-feet in 1989 and 14,000 acre-feet in 1988. Mr. Laymon also indicated that Angostura and Belle Fourche Reservoirs are down to 10% of their storage capacity.

Mike Strub of the Rapid City Public Works Department indicated that the population of Rapid City was 19,000 in 1940; city officials are planning in the next 50 years to expand to serve 120,000 people. The demand is expected to exceed the current water supply by 1991. The City eventually expects to have 15,000,000 gallons (46 acre-feet) per day coming from 12 to 15 wells in the Rapid City area that are now being constructed.

John Mattson, an attorney from Deadwood and one of the operators of the Deer Mountain ski area, commented on the needs of water for the ski industry in the northern Hills. Artificial snow making machines are in use at one area, but more natural and artificial snow is needed from November through March.

John Percevich of the Pactola Pines Marina discussed the problems of the water level in Pactola and its influence on summer activities. There is a moderately large boat industry in the area, which is suffering from the low water levels of the various reservoirs.

Alex Asbridge, representing the City of Custer, discussed the problems of low water level in the Black Hills. Custer was one of the first cities to feel the effects of the water shortage and has had to limit expansion of new businesses because of the low water supply.

Jerry Marsh represented the irrigators of Rapid Valley and mentioned that their largest request for water was in 1985 when they asked for 8,600 acre-feet. The average each summer was a request of 5,400 to 5,500 acre-feet.

Hank Scholtz represented the mining industry. Even though their use of water is substantial, they do not consume much water. Five large scale mining operations use about 200 gallons per minute, about 322 acre-feet per year.

Professor Gabor Vali from the University of Wyoming had discussed Wyoming water problems with the State Engineer and reported the following information. The Belle Fourche and Angostura Reservoirs are fed from water from Wyoming. Keyhole reservoir is in the eastern end of Wyoming. It is at 10% capacity as are the other reservoirs just mentioned. Wyoming is not too concerned about the cloud seeding in the Black Hills or in eastern Wyoming because 90% of the water that goes into Keyhole is reserved for South Dakota, 10% for Wyoming. The state officials see no great problem with cloud seeding in the Black Hills with regard to Wyoming activities.

A short session, Session 2, chaired by Harold Orville of the IAS and held after lunch on Monday was concerned with the scientific background of weather modification. Arlin Super, who has been involved with much of the research in orographic cloud seeding in the western United States with the Bureau of Reclamation, read portions of statements from the Bulletin of the American Meteorological Society (BAMS) and the Weather Modification Association (WMA) concerning the potential for orographic cloud seeding. The BAMS statement suggests a 10-15% increase in orographic seasonal precipitation, while the WMA suggests 5 to 25% increases in seasonal precipitation. Many of the basics of orographic cloud seeding that he described are also covered in the information bulletin (Bulletin 89-3 of the IAS). Dr. Super presented some very interesting results from the Bridger Mountain cloud seeding project that showed cloud seeding effectiveness in reducing the amount of supercooled water in the atmosphere and increasing precipitation on the ground. He indicated that the atmospheric conditions for seeding can often change within one hour or so, so observations of current conditions are quite important. He recommends seeding throughout the storm period even though optimal conditions are not always present. Dr. Super considers the production of silver iodide and its transport to the clouds as a difficult problem. He believes that some projects in the past have failed to actually seed the clouds very effectively.

Paul DeMott of Colorado State University reported on the various seeding materials that can be used on a cloud seeding project. He mentioned four categories of materials: 1) inorganics, such as silver iodide and lead iodide; 2) organics, such as DN or metaldehyde; 3) coolants, such as CO_2, propane, LN_2 or liquid air; and 4) biological, such as bacteria nucleants. Mr. DeMott discussed cloud seeding devices. The release rates from aircraft generators are somewhere around one-half a gram per minute and from pyrotechnics about 20 grams over 40 seconds. He presented activity curves for the materials and compared some of their model results concerning activation of nucleants with their laboratory results. He indicated that solid carbon dioxide could provide 10^{12} to 10^{13} ice crystals per gram of sublimed CO_2 and silver iodide agents 10^{10} to 10^{16} particles per gram.

The last paper in this session was given by Don Griffith of North American Weather Consultants and involved the current winter orographic cloud seeding activities in the United States. Mr. Griffith used reports published by the National Oceanic and Atmospheric Administration (NOAA) to illustrate the amount of activity going on. Reporting procedures are required of all operators so that NOAA can keep track of how much cloud seeding is being done in the United States. Mr. Griffith gave information which indicated 14 states with 33 activities were in operation in 1988; 6 of those states were primarily involved with orographic winter programs. Nearly 63,000 square miles were involved in the target areas in all of these states. In 1989, approximately 13 states were involved in activities with about 56,000 square miles as target areas. Again, six of those states (Utah, California, Nevada, Idaho, Wyoming, Colorado) are involved in orographic activities. Arizona might also be added to that list. Twenty-eight thousand square miles were involved in the orographic cloud seeding.

Mr. Griffith also showed a comparison of weather modification activities from 1978-1988, which indicated the number of activities decreasin from about 70 to a few less than 40 presently. During this time period, the square miles have decreased to about one-fourth of the 230,000 square miles covered in 1978. He indicated that the numbers of programs fluctuate and are a function of the drought cycles and federal funding.

Session 3, chaired by Paul Smith, covered various cloud seeding experiences in the Black Hills and nearby areas. Wilbur Brewer and Harold Orville reported on the spring project in the Pactola watershed. Mr. Brewer indicated that 2,700 grams of silver iodide had been dispensed during 11.5 hours of seeding operations. Harold Orville presented information on precipitation during the month of May, which is the only time that cloud seeding was done over the Pactola watershed. The average precipitation was slightly less in the watershed than outside, but was well within the natural variability of precipitation in the region. However, with so few hours of seeding there could not have been a very significant effect on the precipitation in the watershed. Several factors restricted the number of hours of seeding. They were 1) a 10-day legal delay before the project could start, in which a good seeding situation occurred; 2) aircraft not well enough deiced, so that a large storm situation was missed; 3) aircraft restricted on one occasion to the airport in Bowman, when the runways were not cleared off; 4) time of ferry from Bowman to Rapid City using up some of the potential seeding time; and finally 5) Air Force restrictions on the air space, which eliminated a few hours of potential seeding. Also, under bad weather conditions, the seeding aircraft were restricted from flying below 10,000 feet (msl) over the Black Hills. Consequently, of the potential 40 to 50 seeding hours, only about 11 hours of seeding were actually accomplished.

Harold Orville concluded that the important things learned in the spring project were the following:

1. Ground generators should be added to a project;

2. Well deiced aircraft should be used;

3. Aircraft should be deployed at an airport facility near the Black Hills; possibly Rapid City, Newcastle, or Spearfish;

4. Radar would be very useful for cloud seeding opportunity recognition;

5. Satellite data would also be very useful; and

6. Most importantly, many seedable situations occurred during a month in which precipitation was below average.

Arnett Dennis from the Bureau of Reclamation reported on the experiences of cloud seeding in the summertime in the Black Hills in the 60's and 70's. He stressed that by increasing the cloud tops a slight amount by cloud seeding, 500 meters or so, potential increases in precipitation of 30% might occur. He also mentioned that seeding in one of the target areas in the Rapid Project might affect the other area, so measurements over a large area are needed to evaluate the cloud seeding effects.

In the final paper of this session, Bruce Boe from the North Dakota Atmospheric Resource Board reported on their summer cloud seeding program. They operate with 90% county support, 10% state support. He mentioned four components for a successful project: 1) planning; 2) evaluation; 3) regulation; and 4) education. Their operating budget is about $0.07 per acre over 6,000,000 acres of land.

Stan Changnon spoke at the evening banquet. He made a connection between weather modification and the climate change which seems to be occurring. Many climate models predict a warming and a drying in the northern plains. He warned not to expect a smooth transition from one climate to another. He expects that weather modification will come back in vogue as water shortages become worse. He concluded that the Black Hills is the right place and now is the right time for a responsible long-term cloud seeding research and operational project. The text of his fine talk is available from the IAS.

Session 4, chaired by R. A. Schleusener, was concerned with evaluation and costs of cloud seeding experiments and operations. On Tuesday morning, Professor Gabor Vali discussed the physical evaluation of a project. He said that the main purpose of such an evaluation is to answer the question, "Do we know what we are doing?" The aims of any physical evaluation are to 1) assess the potential of cloud seeding; 2) help design a project to develop proof of concept; 3) support the statistical evaluation that should be done on any project; 4) help in the optimization of the project with regard to targeting, the seeding rates, the type of seeding material, and the safeguards to be used; 5) help in the transfer of the results to other regions; and 6) provide cause-and-effect relationships and proofs. He said that all of these items are functions of the meteorological situation. Physical evaluations are a necessary, even though an expensive part of a cloud seeding project.

Professor Vali mentioned that the main methods and tools used for evaluation were aircraft, radar, microwave radiometers, surface stations for measuring rainfall and snowfall, and tracer studies for finding out where the airflow and the seeding material is going. He mentioned that the synthesis of the observations is helped by models of the seeding situation.

Roy Rasmussen of the National Center for Atmospheric Research and Applied Research Corporation spoke on the use of numerical models for evaluation. He reported on his experience using models in Thailand to help formulate hypotheses for cloud seeding. He used one-dimensional, two-dimensional, and three-dimensional models to aid in this work. His work on mesoscale models has indicated that airflow about mountains can be modeled quite well, and that we have a good chance of also simulating the precipitation processes, both in seeded and unseeded conditions in these models. Many of the cloud models that Dr. Rasmussen discussed are available for the Black Hills have been developed by SDSM&T scientists, and are planned to be applied in the future to Black Hills conditions.

Professor Paul Mielke of CSU discussed the statistical evaluation of a project. He admitted that there are some situations which are "look and wow!" situations. Supercooled fog clearing is an example of that type of evaluation. He discussed target-only design, target-control design, and crossover designs (which he considers the preferable approach). He recommends for the Black Hills a 24-hour experimental unit with eight 3-hour analysis units within each of the experimental units. He would stratify by 6-hour soundings and use the crossover design with 50-50 randomization. He estimates 20 experimental units per season giving 160 analysis units.

Don Griffith spoke briefly on some operational cloud seeding considerations concerning how to mount a program over the Black Hills. He suggested that persons or corporations with experience in conducting winter orographic cloud seeding programs should be contacted and employed in such a program. The Weather Modification Association (WMA) has a certification program and would be a good organization to contact. He stressed that persons or corporations with the available resources, with adequate insurance coverage, and with the proper background are needed to run a good operational project. He thought that the Black Hills was a very excellent area in which to conduct an orographic cloud seeding project. In summary, he stressed that you need qualified personnel, suitable equipment, and a good design to run a successful operational project.

Tom Henderson of Atmospherics Incorporated presented a paper on the cost of an operational project. His financial evaluation was excellent and gave much information of use to the conference personnel. He categorized the expenses into those for personnel, weather data acquisition, radar, aircraft, ground generators and consumables, seeding agents, utilities and leases, transportation, insurance, and communications and setup. He estimated that a Black Hills program lasting seven months and involving five people, one radar, two aircraft, and 40 ground seeding generators would cost nearly $300,000. He estimated that a project for the Pactola Watershed would be approximately $100,000 less.

Paul Smith of the Institute of Atmospheric Sciences discussed the cost of the research component of a cloud seeding project for the Hills. He considered that better climatology of the Black Hills was needed, along with better knowledge of the precipitation processes in the Black Hills. More knowledge about transport of material, and more information about nucleating agents and their activities in the Black Hills were also needed for such a project. A statistical design is needed. Much related research going on regarding cloud seeding in the western United States could be used in the Black Hills project. He stressed that several years of data are needed to conduct a meaningful statistical evaluation. Physical and modeling evaluations are important components of a research project.

The bottom line in his talk was that the cost of a thorough research component would be comparable to the operational cost. A quality radar and research aircraft are very expensive as are the lead scientist and personnel involved in the evaluation and research tasks. The least expensive type of work would be like that done in association with the seeding project in North Dakota, in which historical crop-hail insurance data were analyzed for about $25,000. On the high end of evaluation costs is the federal-state cooperative program for weather modification, with costs of about $500,000 per year on the projects they are studying.

The final paper of the Conference was given by Dr. Roger Reinking of the National Oceanic and Atmospheric Administration (NOAA) who discussed several items concerning operations and research in weather modification plus the budget picture of the federal government. He commented that money for operations would generally not come from the federal government. He mentioned that a user tax has been established in Arizona which provides about $750,000 per year for weather modification. This is based on the acre-foot of water use.

He mentioned two pertinent programs in the National Science Foundation, the mesoscale and the physical meteorology programs, which have about $12,000,000 in research, but that weather modification is a very small part of those programs. The Bureau of Reclamation has been nearly zeroed out in their funds recently but they hope to increase their program in the near future. NOAA's federal-state cooperative program provides about $2.2 million per year for weather modification studies and has been relatively steady for the past few years. He sees no support from NASA, the Department of Defense, or the U.S. Forest Service for weather modification.

The conference ended with a brief discussion of the results and the objectives that Harold Orville had suggested in his opening remarks. It was agreed that many problems still need to be solved in weather modification, but that enough was known to support an orographic cloud seeding project in the Black Hills. There were no critical questions that had to be answered before an operations and research program could be mounted. The main problem was where to find financial support for such a program, and that has not yet been resolved. [Later evaluation for Leonard Duberstein of the Bureau of Reclamation in Billings, Montana, has indicated the cost of a full-season cloud seeding program in the Black Hills to be approximately $300,000 for the entire Hills (competitive bidding might bring that down considerably) and $240,000 or so for the Rapid City watershed. The amount of extra water to be gained is estimated to be of the order of 100,000 to 200,000 acre-feet for the Black Hills and 30,000 to 60,000 acre-feet for the smaller watershed, yielding the cost for an acre-foot in the watershed ranging anywhere from $1.00 up to $8.00 to $10.00. Estimates of extra water in the reservoir are more difficult to make. There are two components to consider: 1) the extra runoff due to the added seeded precipitation; and 2) the extra runoff due to the increased runoff efficiency caused by the cloud seeding. Item (1) involves seeded precipitation only; item (2) involves both seeded and unseeded precipitation. For example, if the runoff efficiency is originally 7%, then the runoff efficiency due to the seeded precipitation may increase 1% to 8%. Item (1) becomes 8% times 30,000 acre-feet equals 2400 acre-feet and item (2) becomes 1% times 360,000 acre-feet (annual average precipitation in the Pactola watershed) equals 3600 acre-feet for a total of 6000 extra acre-feet of water in the reservoir.]

It was certainly the feeling of most of the people at the Conference that a long-term project was needed; a year-by-year project is not the optimum way to go. A well designed five-year operational project with the associated research and evaluation would be desirable.