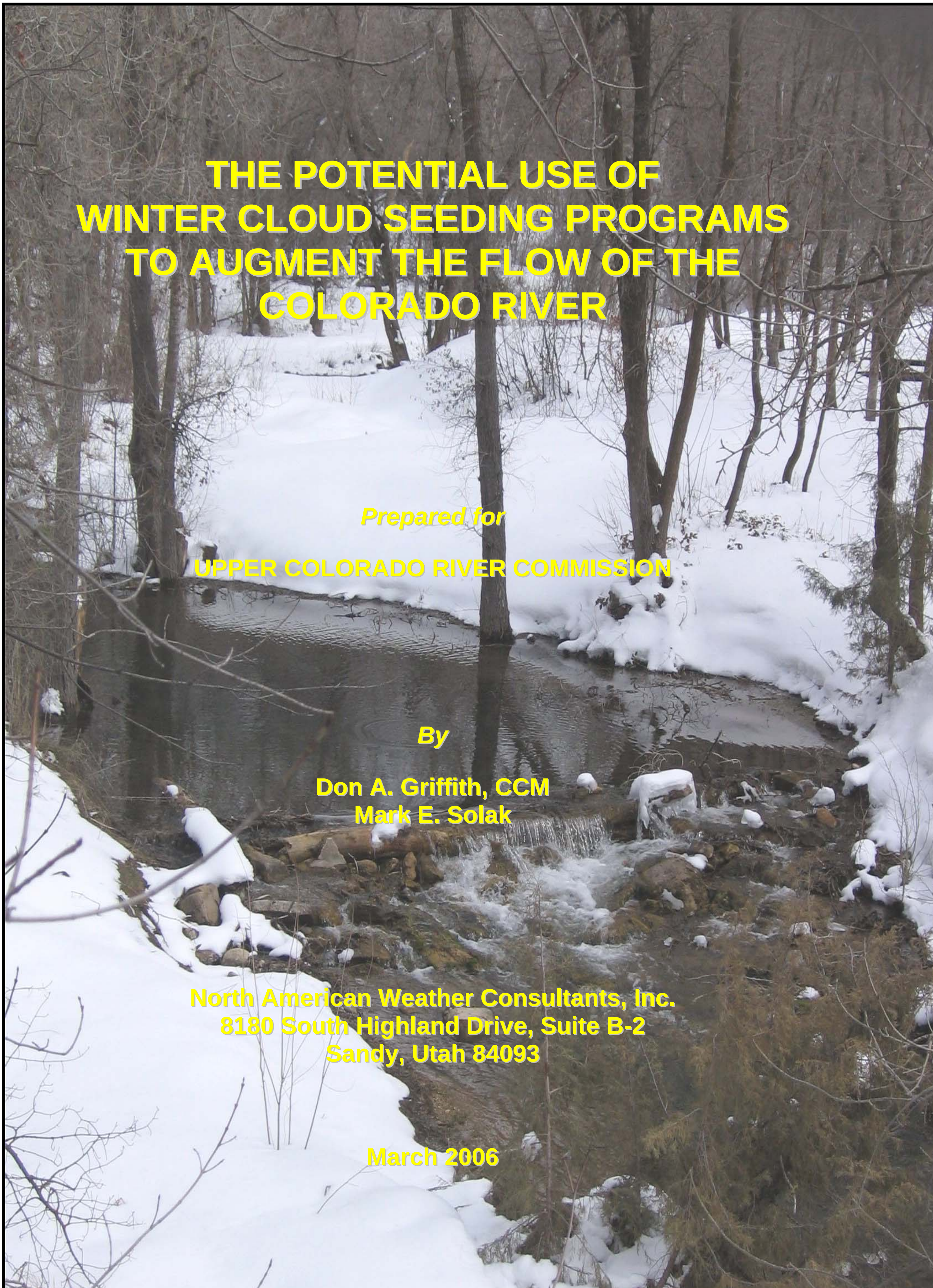

THE POTENTIAL USE OF WINTER CLOUD SEEDING PROGRAMS TO AUGMENT THE FLOW OF THE COLORADO RIVER

Prepared for

UPPER COLORADO RIVER COMMISSION

By

Don A. Griffith, CCM
Mark E. Solak

North American Weather Consultants, Inc.
8180 South Highland Drive, Suite B-2
Sandy, Utah 84093

March 2006

TABLE OF CONTENTS

Figures **Page**

Tables

THE POTENTIAL USE OF WINTER CLOUD SEEDING PROGRAMS TO AUGMENT THE FLOW OF THE COLORADO RIVER

EXECUTIVE SUMMARY

Recent drought conditions and the associated drop in Lake Powell storage has generated renewed interest in means that might be used to better manage the water supplies for the seven basin states that share water from the Colorado River system through the 1922 compact. Means of augmenting the flows of the Colorado are also being examined. One technique that has been frequently mentioned is that of weather modification or "cloud seeding" as it is more commonly known. The Upper Colorado River Commission contracted for the preparation of this White Paper. The goals of this paper were to consider the status of the weather modification field and how cloud seeding could potentially be used to augment streamflows in the Colorado River region.

The potential for use of cloud seeding to increase the amounts of naturally occurring precipitation dates back to some early discoveries and experiments, first conducted in the laboratory and then in the atmosphere, in the late 1940's. Early enthusiasm for such applications led to the conduct of a number of research and operational programs during the 1950's. Some of this early enthusiasm diminished due to difficulties in detecting the effects of seeding on precipitation. In a sense, the potential of cloud seeding was oversold during this period. Additional research and operations were conducted with more realistic expectations beginning in the 1960's and continuing to the present time. Some skepticism remains regarding the effectiveness of cloud seeding, although several professional societies now state that winter time precipitation in mountainous areas can be increased on the order of 10%. Compelling evidence exists for the positive effects of cloud seeding in augmenting water supplies in the west, although proof in the strict scientific sense is elusive.

Several operational winter cloud seeding programs have been conducted in the Sierra Nevada Mountains of California dating back to the early and mid-1950's in a couple of cases and the early to mid 1960's in several other cases. Winter cloud seeding programs have also been operated for a number of years in portions of Colorado, Utah, and Wyoming. For example, programs in Utah date back to 1974. Estimations of the effects on precipitation commonly indicate seasonal increases of the order of 5% to 15%.

This paper identifies areas within the Colorado River Basin where a) new <u>operational</u> winter cloud seeding programs could be developed and b) existing programs enhanced through additional funding to provide additional runoff in the Colorado River system. These activities would include new or expanded programs in the States of Arizona, Colorado, Utah and Wyoming. Streamflow that contributes to Colorado River flows in these areas is primarily generated via melting snow from the higher elevation areas of these states, thus the recommendation for the focus on winter time programs.

A distinction is made between operational programs and research programs. Operational programs are conducted to achieve a specific objective or objectives; in this case, increases in streamflow in the Colorado River Basin. Cloud seeding research programs are conducted to advance knowledge; perhaps to gain a better understanding of how cloud seeding works or to demonstrate the effectiveness of a new seeding approach. Research programs are inherently more costly than operational programs. Research activities could be superimposed on some of the operational programs, as has been done in programs such as the Bureau of Reclamation's Weather Damage Modification Program that is currently active and the earlier National Oceanic and Atmospheric Administration's Atmospheric Modification Program conducted in the 1980's and 1990's. Additional federal funds would be needed to perform such "piggyback" programs, if desired.

The anticipated effects from well designed and conducted operational seeding programs range from 5-15% increases in precipitation. Streamflow model simulations performed by the National Weather Service, River Forecast Center located in Salt Lake City, Utah for the Upper Basin States of Colorado, Utah and Wyoming predict increases of 650,500 acre feet of April through December runoff into Lake Powell during an average year resulting from the conduct of new cloud seeding programs assuming a 10% increase in October through March precipitation. Similar projections for existing operational seeding program areas indicate an estimated average increase of 576,504 acre feet of October through March runoff into Lake Powell in an average year, assuming a 10% increase in precipitation. The total from new and existing areas would be 1,227,004 acre feet. Obviously, the same percentage increases in precipitation in wet years would produce higher amounts of runoff and lower amounts in dry years. Seeding suspensions in very wet winters would limit the expected total increase from such winters. Ample storage would typically be available in the tributary and especially the main stem reservoirs such as Lake Powell to contain any amounts of expected increases in runoff even from wet and very wet winters. It is estimated that an additional 154,000 acre feet of annual runoff could be generated from new seeding programs in the lower Colorado River Basin of Arizona. **The total estimated average potential would therefore be 1,381,004 acre feet.** Some of this potential is currently being realized through the conduct of existing programs in Colorado and Utah, but no attempt has been made in this study to quantify the amount of runoff being generated by these programs. Means of augmenting some of these existing programs are contained in this study. No attempt was made in this study to quantify the additional streamflow that might be generated through such augmentation of existing programs. In a sense, these latter two issues are offsetting; some increases in streamflow from existing programs are currently being realized which would lower the estimated increases whereas enhancements of existing programs operations would increase these estimates.

A preliminary estimate of the costs associated with developing new operational programs and augmenting existing ones for the four states on an annual basis is $6,965,000. Design studies for each of the new potential operational areas are advisable in order to customize cloud seeding activities for specific areas. The above estimated costs include a reservation of 15% of the total funds for evaluations of the effectiveness of the cloud seeding in the new operational areas. Both statistical studies and physical measurements (e.g., detection of silver in snow that could be attributed to the seeding agent, silver iodide) could be performed. **The approximate**

cost of the estimated additional water which could be produced through cloud seeding is estimated to average $ 5.00 /acre foot. Estimates of the value of the additional water could be used to assess the benefit/cost aspect of the proposed projects.

An attractive aspect of cloud seeding programs is that they can be implemented and, if needed, terminated comparatively quickly, since they generally do not involve the development of large permanent infrastructure. Further, operations can readily be suspended during very wet periods and restarted when appropriate.

No significant negative environmental impacts are anticipated from the conduct of such programs, based upon the findings from a number of large scale office and field environmental programs funded by the Denver offices of the Bureau of Reclamation. Several of the field programs have been conducted in the winter environments of California, Colorado, Utah and Wyoming.

When objective assessments of various water resource management and supply options are conducted in similar situations, the weather modification option typically emerges as a most attractive avenue. It appears that this is true for the Colorado River system. This White Paper describes various aspects of the winter cloud seeding option in some detail including a list of recommendations in Section 18.

Recommendations shown in the text are also listed here.

- New operational winter cloud seeding programs should be established in suitable areas in the states of Arizona, Colorado, Utah and Wyoming that are currently not part of active operational programs. This will enhance runoff into the Colorado River Basin. The term "operational" is used to denote programs whose primary goal is to produce additional precipitation. In other words, these programs would not be research oriented, although some research activities might be "piggybacked" on some of these programs should additional Federal or state funding become available. There is precedent for this approach in earlier "piggyback" research activities being added to operational programs in Colorado, Nevada and Utah through Federal funding.
- The development of new programs should follow the existing regulations that are concerned with weather modification activities within each State in which the program is to be conducted. All four states (Arizona, Colorado, Utah and Wyoming) have such regulations.
- Design studies should be conducted to guide the development of potential projects in new areas. Such studies will allow a customized approach to the development of each new program, taking into consideration area-specific factors such as climatology, topography, presence and frequency of seedable conditions, and seeding targeting and social considerations. The State of Wyoming, through their Water Resources Development Commission, has recently adopted this approach in their consideration of new programs in the Wind River, Sierra Madre, Medicine Bow, Salt and Wyoming Mountain Ranges.
- Existing operational programs within the Upper Colorado River Basin could be potentially enhanced. Means of enhancing these effects should be coordinated by the existing program sponsors and operators. Modifications might include additional seeding

equipment, different types of seeding equipment (e.g. aircraft in addition to ground seeding and/or remotely controlled ground generators), and longer operational periods if the full seasonal window of seeding opportunity is not currently being seeded.

- Approximately 10-15% of the budget to conduct new programs should be devoted to evaluations of the effectiveness of the new programs. Two general types of evaluations should be considered; statistical (e.g. historical target/control analyses) and physical (e.g. chemical analysis of snow to detect the presence of silver associated with the release of the silver iodide seeding agent). Additional evaluations of existing programs are not proposed since the program sponsors and/or operators are currently performing their own evaluations.
- Additional simulations of impacts of assumed seeding increases on streamflow should be performed. Such simulation work should be a part of any design studies conducted for potential new seeding areas.
- It is recommended that a multi-year research program be conducted to determine the effectiveness of propane seeding in generating increases in precipitation over large scale areas the size of typical *operational* winter programs. It is recommended that the funding for this research program be obtained from federal sources and consequently the costs of conducting such a research program are not included in the cost estimates contained in Section 15.
- It is recommended that the Seven Basin States support any Congressional Bills that relate to the development of a "coordinated national weather modification research program" such as that proposed in HR 2995 and S 517.
- The Upper Basin States should develop cooperative agreements that feature the development of a "basin-wide water augmentation via cloud seeding program."
- Representatives of the Seven Basin States should consider convening an ad hoc committee to develop the scope of a short-term (3 year) program to augment and fund some of the existing operations and develop and fund some of the potential new programs.
- Representatives of the Seven Basin States should consider beginning discussions regarding cost-sharing and administration of new programs and augmentation of existing programs.

1.0 BACKGROUND

The impact of on-going drought conditions within the Colorado River Basin the past several years resulted in Secretary Norton, Secretary of the Department of Interior, issuing a letter dated May 2, 2005 that outlined the Secretary's intent to develop Lower Basin shortage guidelines and to explore management options of Lakes Mead and Powell. The Bureau of Reclamation published a notice in the Federal Register on June 15, 2005, announcing its intent to solicit comments and hold public meetings to respond to the Secretary's request. A meeting of representatives of the seven Basin States was held in San Diego, California on August 25, 2005. A letter to Secretary Norton was approved at this meeting that addressed three major topics to accommodate the Secretary's earlier request: 1) Coordinated Reservoir Management and Lower Basin Shortage Strategies, 2) System Efficiency and Management, and 3) Augmentation of Supply.

As part of the efforts to augment the supply of the Colorado River, the letter states that "The basin states will work with the Department of the Interior to implement a precipitation management (cloud seeding) program in the basin (both Upper and Lower). Any additional water generated to the Colorado River System will be considered system water. No entity or state will have any claim to any additional supply developed by precipitation management."

This White Paper addresses such a precipitation management program. This paper is focused on winter time precipitation that falls in Colorado River drainages in the states of Arizona, Colorado, Utah and Wyoming, since a large majority of the flow of the Colorado River is generated in this region from precipitation that falls during the passage of winter storms through these areas.

Mr. Don Ostler of the Upper Colorado River Commission contracted with North American Weather Consultants, Inc. of Sandy, Utah to prepare this paper. Two other papers have recently been prepared that are relevant to the current work. One paper was prepared by Tom Ryan of the Metropolitan Water District of Southern California entitled "Weather Modification for Precipitation Augmentation and its Potential Usefulness to the Colorado Basin States" (Ryan, 2005). The second was prepared by the Reclamation Offices in Denver, Colorado entitled "Water Augmentation from Cloud Seeding in the Colorado River Basin" by Hunter, Meyer and Aman, 2005. Some information from both papers has been utilized in the preparation of this white paper.

The intent of this paper is to:

- Provide a brief overview of the status of weather modification technology.
- Document where cloud seeding programs are currently being conducted in the Upper Colorado River region and identify areas in which new programs could be developed.
- Estimate the potential effects upon precipitation and resultant streamflow through upgrading existing programs and establishment of new programs.
- Provide preliminary cost estimates to upgrade existing and establish new programs.
- Provide recommendations for a future course of action.

2.0 INTRODUCTION TO CLOUD SEEDING FOR WINTER PRECIPITATION AUGMENTATION

Since a large percentage of the runoff produced in the Colorado River drainages is produced from melting snow and since cloud seeding over mountain barriers to increase snowfall is one of the weather modification techniques that have demonstrated the strongest evidence of effectiveness, this white paper is focused on winter seeding programs. Summer cloud seeding programs could be considered in some areas, although this white paper does not address these possibilities.

A basic summary of the concept of how cloud seeding is thought to work in wintertime mountainous (orographic) settings is in order. A number of observational and theoretical studies have suggested that there is a cold "temperature window" of opportunity for cloud seeding. Some information contained in a report from the Weather Modification Association (Orville et al, 2004) is paraphrased in some of the following discussions.

Numerous observations in the atmosphere and in the laboratory have indicated that cloud water droplets can remain unfrozen at temperatures well below freezing. These droplets are called supercooled. Thus the phrase supercooled liquid water (SLW) has been coined to refer to the presence of such water droplets in a cloud. In order for water droplets to freeze at temperatures between 30.2^0 F (-1^0C) and -38.2^0 F (-39^0 C) they must come in contact with a foreign particle to cause them to freeze. These particles are called freezing nuclei. The process is known as heterogeneous nucleation. Such nuclei occur in nature and are primarily composed of tiny soil particles. Numerous observations around the world have indicated that the numbers of naturally occurring freezing nuclei that can cause heterogeneous nucleation are temperature dependent. These natural nuclei become increasingly active with decreasing temperatures. Once a supercooled water droplet is frozen, creating an ice crystal, it will grow through vapor deposition from the water droplets surrounding it and, given the right conditions continue to grow through vapor deposition and possibly also aggregation (collection of water droplets on a snowflake as it falls) to form a snowflake large enough to fall from the cloud and reach the ground. Supercooled water droplets in sufficient quantities are the targets of opportunity in order to increase precipitation through seeding.

Studies of both orographic and convective clouds have suggested that clouds whose tops are colder than ~ -13^0 F (-25^0C) have sufficiently large concentrations of natural ice crystals such that seeding will have no effect on precipitation (Grant and Elliott, 1974; Grant, 1986; Gagin and Neumann, 1981; Gagin et al., 1985). There are also indications that there is a warm temperature limit to seeding effectiveness (Gagin and Neumann, 1981; Grant and Elliott, 1974; Cooper and Lawson, 1984). This is believed to be due to the low efficiency of ice crystal production by silver iodide (the most commonly used seeding material) at temperatures greater than 23^0 F ($-5\ ^0$ C), and to the slow rates of ice crystal vapor deposition growth at comparatively warm temperatures. Thus there appears to be a "temperature window" of about 23^0 F (-5^0C) to -13^0 F (-25^0C) where clouds respond favorably to silver iodide seeding (i.e., exhibit seedability). Dry ice (frozen carbon dioxide) seeding via aircraft can extend this temperature window to temperatures just below 32^0 F (0^0C). Seeding by venting liquid propane may also present the potential to expand this window to approximately -2^0 C.

Orographic clouds in the mountainous western states are often associated with passing storm systems. Wind flow over a mountain barrier causes the orographic lift to either produce the cloud or enhance cloud development associated with a migratory feature such as a cold frontal system. *In situ* and remote observations of SLW in orographic clouds (Reynolds, 1988) have indicated significant periods of the occurrence of SLW with passing winter storms. These studies have indicated that the preferred location for the formation of zones of SLW is over the windward slopes of the mountain barriers at relatively low elevations (typically reaching only the approximate height of the mountain barrier). Super, 1990, reporting on measurements of SLW observed in winter research programs in the western U.S. states that, "There is remarkable similarity among research results from the various mountain ranges. In general, SLW is available during at least portions of many storms. It is usually concentrated in the lower layers and especially in shallow clouds with warm tops." Another quote from Super (1990) says: "The tendency for greatest SLW content near the windward slopes of a barrier is clearly shown by Hobbs (1975) from a composite of 22 aircraft missions over the Cascade Mountains, and by Hill (1986) based upon 57 vibrating wire sondes over the Wasatch Mountains of Utah. Holroyd and Super (1984) examined data from many aircraft passes over the flat-topped Grand Mesa of Colorado and showed that SLW was concentrated over the windward slope and barrier top, with higher water contents nearer the surface."

The basic consideration in the development of the design of a winter orographic cloud seeding project is to develop a seeding methodology that will tap this reservoir of SLW to convert water droplets into snowflakes that otherwise would be lost through evaporation over the downwind side of the barrier. In other words, we wish to improve the efficiency of the natural storm system in producing precipitation that reaches the ground.

"If SLW clouds upwind of and over mountain barriers are routinely seeded to produce appropriate concentrations of seeding ice crystals, exceeding 10 to 20 per liter of cloudy air, snowfall increases can be anticipated in the presence or absence of natural snowfall. It has been repeatedly demonstrated with physical observations that sufficiently high concentrations of seeding agent, effective at prevailing SLW cloud temperatures, will produce snowfall when natural snowfall rates are negligible. Seeded snowfall rates are usually light, on the order of 1 mm/hr or less, consistent with median natural snowfall rates in the intermountain West (Super and Holroyd, 1997)."

Figure 1 provides a schematic of how cloud seeding using ground generators on a mountainous winter time program is thought to work.

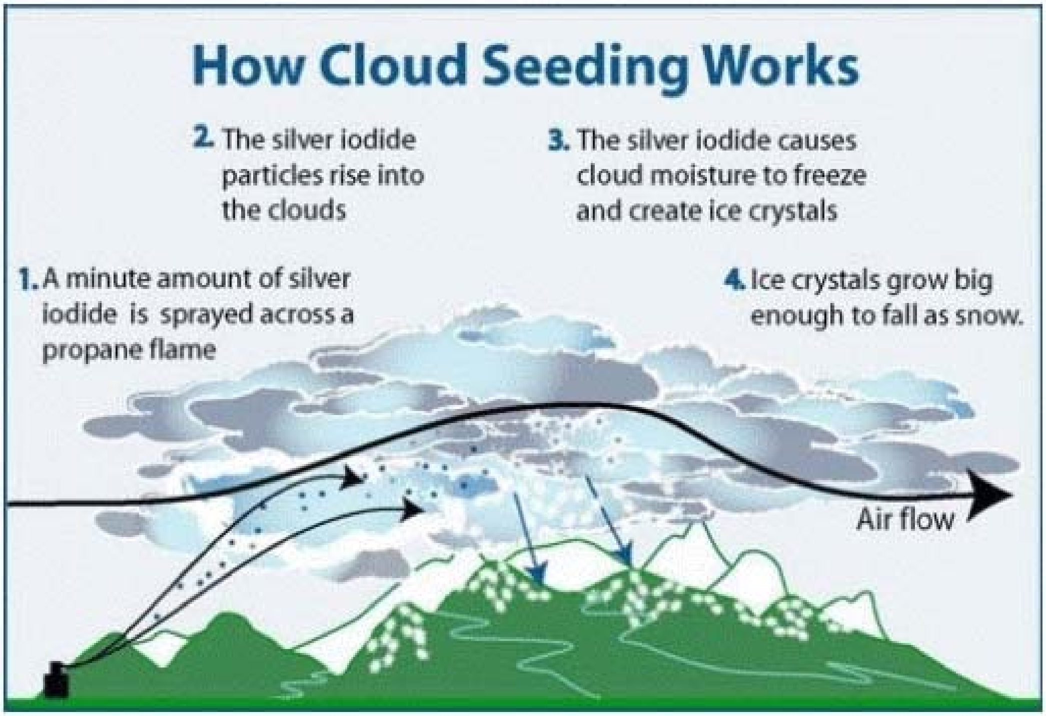

Figure 1. Ground Seeding in a Winter Orographic Setting

3.0 TYPICAL SEEDING AGENTS AND MODES OF SEEDING

3.1 Typical Seeding Agents

The American Society of Civil Engineers, Environmental and Water Resources Institute recently published a document entitled "Standard Practice for the Design and Operation of Precipitation Enhancement Projects" (ASCE 2004). This Standard contains a summary of different types of cloud seeding agents. The summaries for silver iodide, dry ice and liquid propane are as follows.

Silver Iodide

Silver iodide, in combination with various other chemicals, most often salts, has been used as a glaciogenic agent for half a century. In spite of its relatively high cost, it remains a favorite, especially in formulations which result in ice nuclei (IN) with hygroscopic tendencies.

Silver iodide has utility as an ice nucleant because it has the three properties required for field application. These are: (1) it is a nucleant, regardless of mechanism, (2) it is relatively insoluble at $<10^{-9}$ g per gram of water, so that the particles can nucleate ice before they dissolve, and (3) it is stable enough at high temperatures to permit vaporization and re-condensation to form large numbers of functional nuclei per gram of AgI burned (see Finnegan 1998). Thus, the ice crystallization temperature threshold for AgI is about -5°C, significantly warmer than the threshold for most *naturally-occurring IN, which commonly have thresholds closer to -15°C. The chemical formulations of AgI seeding agents may be modified further, so that the resulting IN function at even warmer temperatures (DeMott 1991, Garvey 1975).*

Dry Ice

The direct creation of cloud ice particles by dispensing dry ice (CO_2) pellets into the cloud is another glaciogenic seeding technique which modifies the natural ice formation process by rapidly transforming nearby vapor and cloud droplets into ice (Schaefer 1946, Holroyd et al. 1978, Vonnegut 1981).

Compared with silver iodide complexes, this system has an advantage in that it makes use of a natural substance (frozen carbon dioxide, CO_2, which sublimes at -78°C at 1,000 hPa). However, effective delivery of the CO_2 requires the use of aircraft. The CO_2 is also difficult to store, as sublimation (and therefore loss) is continuous. It is uncommon for dry ice to be the only seeding agent used in a project; it is sometimes used in conjunction with AgI seeding.

Liquid Propane

Liquid propane is a freezing agent much like dry ice. It produces almost the same number of crystals per gram as does CO_2 (Kumai 1982). It cannot be dispensed from aircraft because it is a flammable substance. However, it can be dispensed from the ground if released at elevations which are frequently within supercooled clouds. The United States Air Force has used liquid propane dispensed from ground-based sites to clear supercooled fog at military airports for over thirty years.

Propane seeding was tested as a cloud seeding agent on a winter research program conducted in California for winter snowpack enhancement through the development of a remotely operated ground-based dispenser (Reynolds 1991, 1992). Liquid propane seeding experiments were also conducted on the Utah/NOAA Atmospheric Modification Project (Super, 1999). The interest in propane seeding is due primarily to the fact that propane seeding may be effective at in-cloud temperatures near -2^0 C compared to the effectiveness of silver iodide beginning at temperatures of approximately -5^0 C. Research in some mountainous areas of the west in wintertime indicate that there appears to be rather frequent occurrences of supercooled liquid water at temperatures between 0^0 and -5^0 C (Super, 1999). Since supercooled liquid water droplets are the target of cloud seeding the hope is that seeding with liquid propane could expand the window of seeding opportunities in terms of in-cloud temperatures. A recent randomized research experiment was conducted on the central Wasatch Plateau of Utah testing this agent's possible usefulness in winter time cloud seeding programs (Super and Heimbach, 2005). Results of the randomized treatments indicate seeding increases over a small area during some storm periods with liquid propane. A 2006 update to the ASCE Manual 81 (ASCE, 1995) titled "Guidelines for Cloud Seeding to Augment Precipitation" contains a recommendation that future experimentation needs to be conducted using liquid propane seeding over a fixed target area to demonstrate that increases are occurring over substantial time periods. As a consequence, propane seeding is not recommended for use in the near term as an *operational* cloud seeding agent on the potential Colorado River Basin programs. It is recommended that a multi-year research program be conducted to determine the effectiveness of propane seeding in generating increases in precipitation over areas the size of typical *operational* winter program target areas on a seasonal basis. It is recommended that the funding for this research program be obtained from federal sources and consequently the costs of conducting such a research program are not included in the cost estimates contained in Section 15.

In a similar vein, there have not been any research programs that have demonstrated that dropping dry ice particles from aircraft can produce increases in precipitation over a sizable fixed target area over a substantial period of time. As a consequence, dry ice is also not recommended for use on potential near term operational programs in the Colorado River Basin.

Silver iodide is the seeding agent currently in use in the on-going operational cloud seeding programs in the Intermountain west. Silver iodide is the agent recommended for use on any new *operational* Colorado River programs that may be implemented.

3.2 Seeding Modes

Seeding mode refers to the method(s) used to release seeding agents. Silver Iodide (AgI) seeding material can be released from both ground and aircraft platforms. The ASCE Standard 42-04 describes how silver iodide nuclei may be created as follows:

> *In many cases, AgI is released by a generator that vaporizes an acetone-silver iodide solution containing 1-2% AgI and produces aerosols with particles of 0.1 to 0.01 µm diameter. AgI is insoluble in acetone; commonly used solubilizing agents include ammonium iodide (NH_4I), and any of the alkali iodides. Additional oxidizers and additives commonly include ammonium perchlorate (NH_4ClO_4), sodium perchlorate ($NaClO_4$), and paradichlorobenzene ($C_6H_4Cl_2$). The relative amounts of such additives and oxidizers modulate the yield, nucleation mechanism, and ice crystal production rates.*
>
> *The generation of AgI aerosols can also be accomplished by burning specialized pyrotechnics. In recent years, advances in nucleation physics have resulted in a number of more effective pyrotechnic formulations which produce nuclei that, in addition to having ice nucleation thresholds near -4°C, are also somewhat hygroscopic. The resulting nuclei are not only effective as IN, but they also attract water molecules. This results in particles that in high relative humidities (near saturation) quickly form droplets of their own, which then freeze shortly after becoming supercooled. This condensation-freezing nucleation process generally functions faster than that achieved using simple AgI. Laboratory testing has shown that AgI by itself functions primarily by the contact nucleation process, which is more dependent upon cloud droplet concentration, and consequently, a much slower process (DeMott 1991).*

Ground based silver iodide generators can either be manually operated by local residents or remotely operated from higher elevation, unmanned locations. There are advantages and disadvantages of each type. Silver iodide can also be released from aircraft using either liquid fueled generators or pyrotechnics. Again, there are advantages and disadvantages associated with aircraft seeding. In general, remotely controlled ground equipment or aircraft seeding may be more effective in some situations than lower elevation ground generators, but they will be more costly.

4.0 RECENT WINTER CLOUD SEEDING PRORAMS IN THE WESTERN UNITED STATES

Eleven of the 17 western states conduct operational winter time cloud seeding programs. The term operational is used to describe programs that are designed and conducted primarily to produce an increase in precipitation within designated target area(s). These programs are not research oriented, although designs used in the conduct of the operational programs typically are based upon the results obtained from relevant research programs. Figure 2 provides the locations of operational cloud seeding programs conducted recently in the western United States (WMA brochure). The programs in the plains states are summertime hail suppression and /or rain increase programs. Those from the state of Colorado westward are wintertime precipitation increase (primarily snowpack augmentation) programs. The program in northern New Mexico is in the planning phase. The programs in Wyoming have been designed and funded with some seeding expected to begin this spring. The wintertime programs are described in more detail below.

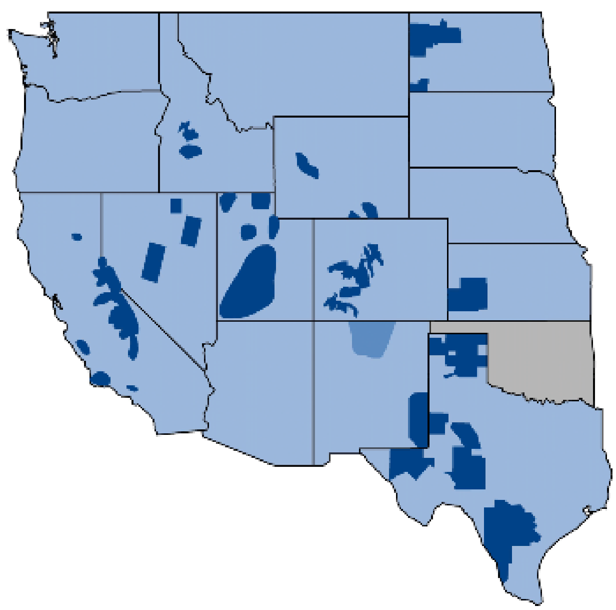

Figure 2. Recent Operational Cloud Seeding Programs in the Western United States

Some of the longest duration cloud seeding programs in the world began in the Sierra Nevada Mountain Range of California. Several of these programs began in the early 1960s, late 1950s and one dating back to 1951. A number of these programs have continued in a continuous or nearly continuous fashion to the present time. Some of these programs are conducted strictly to augment hydroelectric power production while others are multi-purpose (e.g., hydroelectric and irrigation or hydroelectric and municipal water resource driven). A State Water Plan published for the State of California (Department of Water Resources, 2005) contains a chapter on precipitation enhancement. This publication indicates that there have been 12-13 active operational winter cloud seeding programs in recent years covering approximately 13,000 square miles. Most of these programs have been conducted in the Sierra Nevada region although programs have also been operated in some coastal counties (i.e., Los Angeles, Monterey and Santa Barbara Counties). The California Water Plan contains an interesting statement, which is as follows:

Four of the existing cloud seeding projects in California are sponsored by hydroelectric utilities. These four projects probably account for about a third of the estimated statewide water production by cloud seeding. There is some concern that if these power plants are sold, either as part of deregulation or other reasons, new owners may not be interested in continuing cloud seeding. This would result in some loss in water supply for downstream users who have been indirectly benefiting from the added water. The State Public Utilities Commission is aware of this possibility and has tried to ensure, as a condition of transfer, that the weather modification would continue.

There have been 4-5 winter operational cloud seeding programs conducted in Nevada in recent years. Some of these programs date back to 1981. Targeted areas include drainages on the eastern slopes of the Sierra Nevada Range (Lake Tahoe, Truckee, Carson and Walker Rivers), the Ruby Mountains (Upper Humbolt River), the Tuscarora Mountains (South Fork of the Owyhee River), and the Toiyabe Mountains (the Reese River).

Winter operational programs conducted in Utah date back to the early 1950's with more recent programs running from 1974 to the present. Normally 3-4 different projects have been active in recent years, covering approximately 13,250 square miles. Targeted drainages include portions of the Sevier, Virgin, Bear, Duchesne, Weber and Provo Rivers.

Programs conducted in Colorado also date back to the 1950s. Programs have recently been conducted in the Central Colorado Rockies (Upper Colorado and Rio Grande Drainages), the Grand Mesa area (tributaries of the Gunnison and Colorado Rivers), the upper Gunnison River drainage, the San Juan Mountains (Dolores, La Plata, Las Animas, Los Pinos, Piedra, and San Juan drainages). These programs cover approximately 6860 square miles. Smaller programs have also been conducted to benefit some ski areas (Aspen, Vail-Beaver Creek, and Telluride).

Wyoming has one long-term program that has been conducted in the southwest portion of the Wind River Range since 1975. The Wyoming Water Development Commission has funded two feasibility/design studies for winter orographic seeding programs. The design for the first study (WMI, 2004) conducted for the Wind River, Medicine Bow and Sierra Madre Ranges was accepted and a five year program initiated in 2005 at an estimated cost of approximately 8.8 million dollars. Its design includes several features more commonly associated with research programs. The second feasibility/design study is being conducted for the Salt River and Wyoming Ranges in western Wyoming.

The State of Idaho has also been the site of several winter programs in recent years. Several counties in eastern and southeastern Idaho were involved in programs in the mid to late 1990s. Another program has been conducted over the upper Boise River drainage for several years dating back to the mid 1990s. Idaho Power designed and subsequently has operated a program in the upper Payette River drainage in central Idaho. Three seasons of operations have been completed through 2005. This program, similar to the Wind River, Medicine Bow and Sierra Madre program in Wyoming, has also included some more research oriented activities. The combined size of the Idaho Power and Boise River project areas is approximately 4,500 square miles.

Evaluations of these various winter programs have typically indicated increases in winter precipitation in the range of 5-15%.

5.0 SUMMARY OF RESEARCH EFFORTS

Tom Ryan, affiliated with the Metropolitan Water District of Southern California, prepared a White Paper (Ryan, 2005) entitled "Weather Modification for Precipitation Augmentation and its Potential Usefulness to the Colorado Basin States." Portions of a section from this paper are provided in the following with the author's approval.

This section provides a description of the agencies that have, currently do, or may participate in WxMod activities. For those agencies that do have ongoing programs, the program is briefly described.

5.1 Bureau of Reclamation. *The need for additional water in the Colorado River Basin has been recognized and studied for many years. The Secretary through the Bureau of Reclamation (Reclamation) is specifically charged with the responsibility for development of the water resources of the Colorado River Basin. Reclamation has the longest history of any Federal agency in WxMod research, dating back to the 1960s. A number of options have been considered to provide additional water supplies for the Colorado River Basin. These options include importation, desalination, evaporation suppression, vegetation management, and precipitation management (weather modification by cloud seeding). Of all the options, precipitation management appears to be one of the most cost effective and economical means of providing additional fresh water supplies. Cloud seeding technology, when properly applied, appears to have the potential to increase winter snowpack in the mountainous areas of the Colorado River Basin (U.S. Department of the Interior (DOI), 1993).*

Weather Damage Modification Program (WDMP). WxMod research has been in significant decline since the 1980s. This decline was briefly interrupted in fiscal year 2002, when Congress authorized funding of the WDMP and specified that it be administered by Reclamation. The primary goal of the program is to "improve and evaluate the physical mechanisms... and to enhance water supplies through regional weather modification programs..." There was no funding for this program beyond fiscal year 2003. In order to participate, states were expected to match federal funding and piggy-back their research on existing operational weather modification projects. The WDMP received a total of $2 million in federal funds over two years and some significant research has been accomplished by the seven *states involved. The program provides an excellent model of federal/state collaboration and funds – leveraging that can apply to the national cooperative federal and state program proposed in the House and Senate.*

Three programs have been funded through this program related to winter orographic seeding efforts in Colorado, Nevada and Utah. Work is either finished or being completed on these programs.

Work conducted in Colorado was concerned with the utilization of the Colorado State University's RAMS model to conduct modeling over seeded areas in the State, simulate generator output and transport, develop forecasts for seeded and non-seeded days, and evaluate model predictions of precipitation. The RAMS model did not reliably predict the natural snowfall and, as a result, the predictions of any seeding effects were inconclusive (Colorado Conservation Board, 2005).

Work conducted in Nevada focused upon the following: remote sensing of supercooled liquid water to quantify cloud seeding potential over a selected watershed, application of mesoscale modeling to evaluate seeding effectiveness, evaluation of seeding effectiveness through physical and chemical analysis of snowpack, hydrologic modeling to estimate impacts of seeding, and characterization of natural and seeded cloud regions using microphysical aircraft measurements. A final report on the findings of this work has not been completed at the time this white paper was written.

Work conducted in Utah involved randomized field testing of propane seeding and exploration of the impacts on precipitation. Releasing liquefied propane through a nozzle results in a zone of supercooled air in which unfrozen water droplets will be frozen. This process can lead to the formation of artificially generated snowflakes. Results of this research were positive with the indication that the seeding did produce increases in precipitation in a small area represented by three nearby precipitation gage sites (Super and Heimbach, 2005). The authors speculated that extrapolation of these results over a season and over larger areas with more dispensers might result in precipitation increases on the order of 10%.

The WDMP program managers expect this program to end in early 2006 in the absence of further funding from either federal sources or non-federal partners. Final reports from most WDMP states have been completed and are available from Reclamation

Colorado River Enhanced Snowpack Test (CREST). The CREST was planned to operate for eight years but was not implemented because of declining federal support of WxMod research and some wet years in the late 1980s and early 1990s.

5.2 National Oceanic and Atmospheric Administration (NOAA). *From 1986 through 1995, the NOAA Federal-State Atmospheric Modification Program funded weather modification research in six states, at a level of about $500,000 per year per state. The funding was used for research components, and was split between winter orographic and warm season programs and included cloud seeding experiments using both silver iodide and liquid propane. The breadth of the research was significant and several advances related to winter orographic cloud seeding* *are worth noting. In Arizona a new polarized radar technique was used to track the dispersion of airborne seeding plumes and the evolution of seeded ice crystals in naturally precipitating clouds. Seeding trials using ground releases of silver iodide and propane on the Wasatch Plateau of Utah produced considerable direct evidence of ice crystal and snowfall enhancement. In Nevada and California a new dual-tracer chemical technique was developed to assess the impact of seeding on winter snowpacks. Several state projects used numerical models, verified by observations, to study the transport and dispersion of seeding material over mountainous terrain. The results of these studies were published in numerous peer-reviewed journal articles.*

6.0 POTENTIAL ADDITIONAL RESEARCH-ORIENTED PROGRAMS TO BE CONDUCTED IN THE WEST

There was the potential to continue funding for research and development work in weather modification contained in Senate Bill S-517 and a companion House Bill HR-2995. The purpose of these acts would be to "develop and implement a comprehensive and coordinated national weather modification policy and a national cooperative Federal and State program of weather modification research and development." The act proposed funding of $10,000,000 per year for each of the fiscal years of 2005 through 2014. The Western States Water Council passed a resolution supporting these acts at a meeting held in Seattle Washington on July 15, 2005. The adopted resolution states that "The Western States Water Council strongly supports enactment of the Weather Modification Technology Transfer Act of 2004 (S. 517 and H.R. 2995), with the addition of a provision assuring compliance with applicable state laws." Senate Bill 517 was heard by the Committee on Commerce, Science and Transportation on November 10, 2005, and has been placed on the Senate Legislative Calendar under General Orders, Calendar No. 319. The amended S. 517 is markedly different from the original, mainly in the creation of a subcommittee (chaired by a NOAA representative and also consisting of NSF and NASA members) to oversee the research program, and with the original Board now being formed to advise the subcommittee. The subcommittee is also given the role of advising on funding required to carry out the research plan that evolves. The $10 million for 10 years funding component was also removed.

The State of Wyoming, through their Wyoming Water Development Commission, recently approved a five year plan to conduct a weather modification program over the Wind River, Medicine Bow and Sierra Madre Mountain Ranges (see Section 4.0). The estimated cost of this work is $8.8 million. This program will contain some research oriented activities including the use of a sophisticated numerical cloud and diffusion model in both real-time and assessment phases, physical sampling of the clouds and the snowpack, and independent evaluations of the apparent effectiveness of the seeding activities.

The California Energy Commission has funded some public interest weather modification research activities and is considering additional proposals. The general goal of this work would be to help optimize the effects of operational winter cloud programs currently conducted in the Sierra Nevada Range of California. A primary vehicle for such optimization would be applied weather modification research, piggybacked on operational programs. According to the California Water Plan (2005) there were eleven operational programs conducted in California during the 2002-2003 winter season.

The New Mexico Weather Modification Association was formed in 2004. This Association is planning winter cloud seeding programs that may be conducted in the northern mountains of the state. The Association is seeking funding from the state legislature to initiate a pilot program.

7.0 INDICATED RESULTS FROM WINTER CLOUD SEEDING PROGRAMS IN THE INTERMOUNTAIN WEST

Indicated results from both research and operational winter programs in the Intermountain West are summarized in the following:

7.1 Research Programs

Climax I and II

Researchers at Colorado State University conducted two wintertime orographic cloud seeding experiments during the 1960's: Climax I (1960-1965) and Climax II (1965-70). The research included randomized seeding experiments, using ground based silver iodide (AgI) generators, and parallel physical studies of cloud and seeding processes. Climax I indicated a positive precipitation difference of about 6% and in Climax II the difference was about 18%, but with a high probability that either of the differences could be due to chance. Evidence was found for increases of approximately 25% from seeded systems when warmer orographic cloud-top temperatures prevailed (indexed by the 500 mb temperature being $\geq -20^{0}$C), with no difference indicated when temperatures were colder. The analysis results were reported in Mielke (1971) and a reanalysis by the same author (Mielke et al, 1981). Re-analyses of Climax I & II by Rangno and Hobbs (1987, 1993) yielded lower, but still positive, indications of a seeding effect.

Colorado River Basin Pilot Project (CRBPP)

A five-year randomized cloud seeding experiment was conducted by the Reclamation offices in Denver, Colorado during the early 1970's in the San Juan Mountains of southwestern Colorado, to determine whether the experimental procedures applied in the earlier Climax work would be effective in an operational mode. Seeding was accomplished using ground-based AgI generators. A formal statistical analysis based on 24 hour blocks of precipitation data from 71 experimental treated days and 76 experimental control days found no significant difference between precipitation on seeded and unseeded days. However, *a posteriori* analyses based on shorter (6hour) data intervals indicated that strongly positive seeding effects may have been achieved during periods of relatively warm-topped cloud occurrences, as expected from the Climax experiment. The results of the *a posteriori* analyses suggested that a flawlessly conducted program of selective seeding could increase overall winter precipitation by about 10%-12%. These results are presented in Elliott et al, (1978). The results of the 24 hour block analysis may have been negatively affected by seeding material targeting difficulties during more stable storm phases as detailed by Marwitz (1980).

Bridger Range Experiment

A randomized exploratory seeding experiment was carried out in the Bridger Range of southwestern Montana during the winters of 1969-72. The seed mode was ground-based AgI generators located at mid-mountain or higher locations to avoid seeding material trapping by lower stable layers. Airborne plume sampling and silver-in-snow analysis provided evidence of successful targeting of the seeding material. A *post hoc* statistical analysis using control gage data indicated about15% more seasonal target area precipitation than predicted. Snowpack data analysis indicated positive effects of the same seasonal magnitude. The experiment is summarized in Super and Heimbach (1983).

7.2 Operational Programs

Utah Power and Light

A winter snowpack augmentation seeding project was conducted by North American Weather Consultants (NAWC) for Utah Power & Light (UP&L), focused on portions of the Bear Lake watershed, including the Thomas Fork and Smith's Fork region of Wyoming. The project used ground-based solution-burning AgI generators and was conducted during the periods of 1955-1970, 1980-1982, plus 1989 and 1990. An historical target/control mathematical evaluation of snowpack during the 18 winter seasons through 1982 (Griffith et al, 1983) indicated a positive difference of 11 percent, reported as statistically significant at the .055 level using the one-tailed Student's t test. That analysis also presented a convincing double-mass plot of target and control seasonal snowpack data encompassing the pre-project (statistical base period) years and the subsequent seeded and embedded not-seeded years.

Utah Projects

NAWC has been the cloud seeding contractor for a number of Utah winter snowpack augmentation projects covering much of the mountainous terrain in the state since the mid-1970's (Griffith et al, 1991; Griffith et al, 1997; Stauffer, 2002). These projects employ ground-based AgI solution-burning generators in valley and foothill locations. Numerous mathematical evaluations have been conducted of those projects, some now spanning more than 25 years. The results of the historical target/control analyses of possible seeding effects averaged over multiple season range from 9% to 21% increases, with a gradient of apparent effects increasing from south to north for the project areas located west of and on the upwind slopes of the primary north-south oriented Wasatch Range.

Nevada/Desert Research Institute Projects

The State of Nevada, through the Desert Research Institute (DRI) has conducted cloud seeding since the 1960's, beginning in the Tahoe area and expanding to other areas in more recent decades. These projects are an outgrowth of DRI weather modification research programs funded through Reclamation and the National Oceanic and Atmospheric Administration. The projects employ automated ground-based AgI solution-burning generators and have been in operations since the 1980's. DRI's estimates of seasonal seeding effectiveness have indicated increases ranging from 4% to 10%.

Boise River Board of Control

NAWC has operated an operational cloud seeding project for the Boise River drainage in southwestern Idaho for several years beginning with the winter of 1992-93. The seed mode involves ground-based AgI solution burning generators in valley and mountain locations. Mathematical, target/control, estimations of seeding effectiveness over eight winter seasons indicate average seasonal increases of the order of 5% to 8% (Griffith et al, 2005).

Idaho Power Company

The upper Payette River drainage in western Idaho has undergone cloud seeding since 2003, through a project conducted by Idaho Power. Automated ground-based AgI solution-burning generators and aircraft are employed to conduct the seeding. The project has included some interesting research components, including trace chemistry analyses of the snowpack. Estimates of seasonal (three seasons) seeding effectiveness indicate an average of about 7% to 9% increases (Idaho Power, 2005).

Upper Gunnison River

NAWC has operated a program for the upper Gunnison River Basin located in west central Colorado for two full winter seasons and portions of a third (2002-2005). The seed mode involves ground-based AgI solution burning generators in valley and mountain locations. Historical target/control estimated average increases over the past two winter seasons of about 12-14% in target area snow water content (Griffith et al, 2004; Griffith et al, 2005) utilizing the historical target/control evaluation technique.

Denver Water

The Denver Board of Water Commissioners sponsored a winter program during the 2002-2003 and 2003-2004 winter seasons. The program was placed into a stand-by status for the following two winter seasons. This program is being conducted by Western Weather Consultants of Durango, Colorado. Ground-based silver iodide generators are used to seed the upper Colorado River drainage located on the west slopes of the Rocky Mountains west of Denver. NAWC was contracted by the Denver Board of Water Commissioners to conduct an independent evaluation of the first season of the seeding program (Solak et al, 2003). This evaluation indicated increases in target area precipitation and snowpack in the 15-16% range.

Vail Ski Area

Western Weather Consultants of Durango, Colorado has conducted a winter cloud seeding program for the Vail Ski area located in the Central Colorado Rockies since the 1977-78 winter season. A network of ground based silver iodide generators is used to seed this area. An analysis of the apparent seeding effects for this program covering a ten year period (1985-1995) was prepared by Western Weather Consultants (Hjermstad, 2001). This analysis indicated the following:

- An increase in precipitation in the target area of 7-15%.

- The most favorable wind directions yielding the highest percentage increases were from west though north.
- For seeded systems with westerly winds (from 240^0 to 295^0) much of the precipitation increases seemed to be due to an increase in the density of the snow in the target area.
- For seeded systems with more northerly wind directions the increased precipitation appears to result from additional inches of snowfall in the target area and the snow density becomes similar to not seeded areas.

Summary

The results cited from both research and operational programs conducted in the Intermountain West suggest a reasonable expectation of 5-15% increases in winter precipitation from properly designed and conducted winter programs. This range of increases is consistent with those included in weather modification policy statements of the American Meteorological Society, the Weather Modification Association and the World Meteorological Organization.

8.0 TYPICAL BENEFIT/COST RATIOS

In the design of new winter cloud seeding programs, the estimated value of the additional water expected via implementation of the seeding program is frequently compared to the estimated costs of conducting the program. This information, frequently expressed as a ratio of benefits/costs, can be used to assess whether the program appears to be feasible in an economic framework. Other assessments may be necessary to determine if a proposed project appears feasible scientifically. Benefit/cost ratios greater than 1.0 are obviously desired. An update to a publication of the American Society of Civil Engineers (ASCE, 1995) published in 2006 recommends a ratio of approximately 5/1 to consider a program feasible. Some operational programs are currently being conducted with somewhat lower ratios (e.g., for example approximately 3/1) which is a decision that certainly can be made by sponsors of programs. These criteria are directed at operational programs. Research programs are more expensive to conduct and typically do not undergo such an economic justification.

Some estimates of benefit/cost ratios of winter operational (or primarily operational) programs have been cited in the literature. Henderson (2003) examined six long-term programs being conducted in California. He estimated benefit/cost ratios, primarily driven by the value of additional hydroelectric energy due to enhanced streamflows, range from 13/1 to 61/1 for increases of 2-9% in additional runoff. These would be primary benefits. As is often the case in these types of assessments, there will also be secondary benefits. For example, since the generation of hydroelectric energy is non-consumptive, the additional streamflow could also be subsequently used for irrigated agriculture or culinary water purposes. The estimated average cost of producing a 6% increase in streamflow was $3.27 per acre foot for these six programs.

An analysis of benefit/cost ratios on a four season program conducted on the upper Boise River drainage of west central Idaho yielded an estimated benefit/cost ratio of 9.7/1, associated with an estimated average increase of 12% in snow water content (Griffith and Solak, 2002). Again, this was strictly based upon enhanced hydroelectric generation; the value of the additional water for downstream uses was not included in the calculation. The estimated average cost of producing the additional streamflow was $0.44 per acre foot for the four seasons.

A feasibility/design study was performed by Weather Modification, Inc. (WMI) of Fargo, North Dakota for the Wyoming Water Development Commission (WMI, 2005). This study included estimates of the amount and value of water that might be produced from a winter cloud seeding program in the Wind River, Medicine Bow and Sierra Madre Ranges of Wyoming. The calculation of the amount of water was driven by an assumed 10% increase in precipitation and resultant 8% increase in runoff. A range of estimated benefit/cost ratios of 2.4/1 to 4.7/1 were the result using different assumptions. The associated estimated cost of producing the additional runoff was $7.91 per acre foot.

9.0 SUMMARY OF CAPABILITY STATEMENTS

The principal societies or associations concerned with weather modification capabilities in all or part include the following.

- The Weather Modification Association (WMA)
- The American Meteorological Society (AMS)
- The World Meteorological Organization (WMO)
- The American Society of Civil Engineers (ASCE)

Each group maintains and publishes a policy or capability statement regarding weather modification in its primary categories. Excerpted from their overall statements, the statements of each organization pertaining to winter precipitation augmentation are provided in Appendix A.

From the organizational statements contained in Appendix A, the following key points regarding the current status of winter orographic seeding for snowpack augmentation emerge.

- Of the primary categories of cloud seeding for precipitation increase, seeding of winter orographic storm systems seems to offer the best prospects for increasing precipitation in an economically-viable manner.
- Strong (albeit largely non-randomized) statistical evidence exists for (winter) seasonal increases of the order of 5% to 15%.
- Many of the microphysical links in the winter precipitation augmentation chain of events have been documented via various physical experiments and observations.

10.0 AREAS WITHIN THE COLORADO RIVER BASIN WITHOUT CLOUD SEEDING PROGRAMS CURRENTLY BUT WITH GOOD SEEDING POTENTIAL

Section 4 of this paper briefly describes on-going operational winter cloud seeding programs in the west. Some of these programs are already operating in drainage areas that are tributary to the Colorado River. There are additional areas within the four states of Arizona, Colorado, Utah and Wyoming that may be considered for the establishment of new winter cloud seeding programs. Some earlier studies performed for Reclamation documented areas within these states that were considered as potential operating areas. Two of these studies were 1) "The Impacts of Snow Enhancement" complied by Leo Weisbecker of the Stanford Research Institute, 1974, and 2) "Twelve Basin Investigation" by North American Weather Consultants, 1973.

Figure 3, taken from a recent report prepared by Reclamation (Hunter et al, 2005), shows current and potential cloud seeding areas within the four states. Table 1 (also from that report) provides names of the areas of the *existing* programs according to the numbering scheme used in Figure 3. The basis for selection of *potential* areas was based primarily on selection criteria contained in a Reclamation proposal (Super et al, 1993) for a research oriented cloud seeding program to be conducted in the Upper Colorado River Basin which was identified by the acronym CREST (Colorado River Enhanced Snowpack Test). The criteria used to identify potential target areas were as follows: 1) a 9000 foot elevation base threshold 2) the potential mountain barrier must have at least 5km (~3 statute miles) east-west extent and 3) the potential mountain barrier has to be located largely or wholly outside designated wilderness and National Park areas. These criteria were somewhat more restrictive than those used in the two earlier Reclamation reports. Table 2 (also from Hunter et al, 2005) identifies the *potential* new areas in Figure 2 according to the numbering scheme used in this figure. The west slopes of the Wind River Mountains in Wyoming are included in Table 2 since there is currently no seeding being conducted in this area. The Wyoming Water Development Commission has, however, awarded a five year contract for seeding in this area. Seeding activities are likely to begin during the 2006-2007 winter season. The area covered by those potential target areas included in Table 2 cover approximately 5,172 square miles. For comparison purposes, the existing projects depicted in Table 1 cover approximately 11,688 square miles.

The operational programs being conducted in Utah utilize a lower 7000 foot threshold to define the target areas. This contour level is proposed to define the potential target area covering the north slope of the Uinta Mountains, the Lasal Mountains, the Henry Mountains (called Mt. Ellen in Hunter et al, 2005), the east slopes of the Boulder Mountains, and the Abajo Mountains in Utah (numbers 20-23 in Figure 2 and Table 1). It is also proposed that the 7000 foot contour be used to identify potential target areas in Arizona. Part of the rationale for inclusion of this lower elevation area is based upon some earlier field studies conducted by Reclamation indicating potentially favorable seeding conditions in this area (Super et al, 1989). These changes would enlarge the potential areas in Utah and Arizona (numbers 26-29) and would also introduce a new area in Arizona; the western end of the Mogollon Rim area located northeast of Phoenix. There is another area located in the extreme upper drainage of the Colorado River located in and near Rocky Mountain National Park that was excluded in the Hunter et al, 2005 analysis. It is argued that this area should be considered, so as to include all areas that provide substantial contributions of streamflow to the Colorado River. There are a number of on-going winter cloud seeding programs being conducted in the western United States that contain wilderness areas and/or National Parks within the boundaries of the intended target areas.

The recommended inclusion of lower elevation areas in Arizona would probably require the use of aerial seeding instead of ground based seeding due to warmer temperatures during storm periods at those latitudes (e.g., the effective level for silver iodide seeding will be at higher elevations which would be more difficult to reach consistently with seeding materials released from ground generators), complicated by the fact that ground releases would be made from lower elevations). This same conclusion was reached in a Reclamation report (Super et al, 1989) that examined the seeding potential of the Mogollon Rim area in Arizona. The following statement is made in the abstract from this document: "Aircraft seeding would likely be required for a large fraction of the Arizona storm clouds." There are other new areas in Utah that would potentially benefit from an aerial seeding approach: 1) the north slope of the Uinta Mountains located in northeastern Utah and the LaSal, Abajo and Henry Mountains located in southeastern Utah. The need to consider aerial seeding for the north slopes of the Uintas is driven by the fact that there are few residences in the upwind area that could be used as manual generator sites. An option could be the installation of a network of remotely controlled, ground generators. The other mountain ranges identified in southeastern Utah are rather small in their horizontal extent, making the targeting of seeding materials released from ground generators problematic; thus the recommendation for aerial seeding. Aerial seeding in all of the above areas is considered feasible since the areas upwind of these potential target areas are at lower elevations which would allow the aircraft to safely fly at low enough altitudes to effectively treat the zone of supercooled liquid water that typically forms over the upwind sides of the mountain barriers.

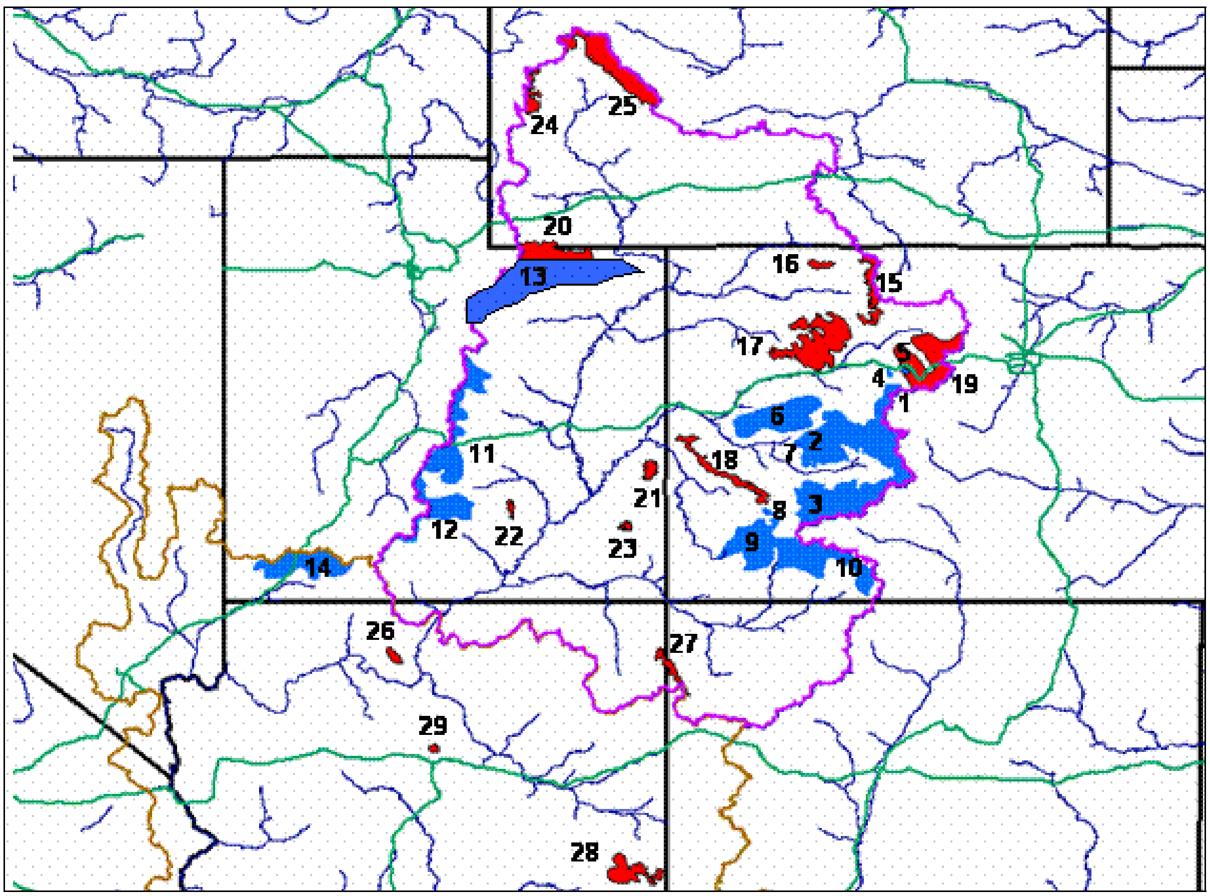

Figure 3. Existing (operational) cloud seeding target areas (blue) and potential target areas (red). Areas are indexed with numbers corresponding to those in Tables 1 and 2, respectively. Magenta and brown polygons are Upper and Lower Colorado River basin outlines, respectively.

Table 1 Existing Target Areas

Colorado	Utah
1. Upper Arkansas†	11. Fishlake Mtns.†
2. Gunnison North	12. Boulder Mtn. †
3. Gunnison South	13. Uinta Mtns. South
4.Vail	14. Dixie Natl. Forest†
5.Beaver Creek	
6. Grand Mesa North	
7. Grand Mesa South	
8. San Miguel Mtns.	
9. Western San Juans	
10. Eastern San Juans	

† Portion of area outside Colorado River Basin

Table 2. Potential Target Areas

Colorado	Utah	Wyoming	Arizona
15. Park Range	20. Uinta Mtns. North Slope	24. Wyoming Range	26. Kaibab N.F.#
16. Elkhead Mts.	21. La Sal Mts.	25. Wind River Mtns. West#	27. Chuska Mts. (AZ/NM)
17. White R. Plateau	22. Mt. Ellen#		28. White Mts.
18. Uncompahgre Plateau	23. Abajo Pk. #		29. San Francisco Peaks#
19. Central Rockies @			

Areas not identified in CREST document
@ Area was operationally seeded in previous years by Denver Water utility

11.0 COULD THE EFFECTS FROM EXISTING CLOUD SEEDING PROGRAMS IN THE COLORADO RIVER BASIN BE ENHANCED WITH ADDITIONAL FUNDING?

Figure 3 (from section 10) indicates that several potential areas for winter cloud seeding programs in the upper Colorado River Basin are already being targeted by existing programs. An obvious question is whether there could be additions made to these existing programs in order to provide higher amounts of precipitation and runoff? The short answer to this question is yes. Operational programs seldom enjoy the luxury of having enough funds to optimize the effects of cloud seeding within their target areas. Possible additions would generally fall under two categories: 1) addition of different types or greater numbers of seeding equipment and amount of seeding, and 2) extension of seasonal operational periods.

There are several possibilities under the first category. Perhaps the addition of higher elevation, remotely-controlled silver iodide generators would be desirable. Additional ground generators may be added to an existing program if the spacing between generators is not sufficiently close to produce consistently overlapping seeding plumes in the seedable cloud regions.

The addition of one or more seeding aircraft may be appropriate, although this decision is driven by the characteristics of the individual target areas. If there are mountain ranges upwind of the existing target areas, this may mean that aircraft cannot be flown low enough in order for the seeding material to enter the desired cloud regions, which are typically found at low elevations on the windward sides of the target barriers. Two areas that may benefit from the addition of seeding aircraft are the San Juan Mountains of southwestern Colorado and the south slope of the Uinta Mountains of northeastern Utah. There are no major upwind barriers that could present safety considerations for these two areas and both areas generate considerable runoff.

Some programs, due to funding constraints, may be unable to operate for the entire winter season. Such programs will be typically operated during the “best” period based upon climatology. For example, a program may be currently operating from December through March. Additional precipitation could probably be produced if the program was expanded to operate during the months of October, November and April provided that suitable conditions (e.g., temperatures and presence of supercooled liquid water) exist for significant durations during these months.

12.0 POTENTIAL IMPACTS DURING DRY, NORMAL AND WET WINTERS

A question that is asked rather frequently is “What are the potential effects of cloud seeding in dry, normal, and wet years?” This question is often asked during a drought period that is affecting a given area. This is certainly a legitimate question. Those who have sufficient knowledge of cloud seeding will not advocate the technology as one that is going to “bust” or “solve” the drought problem. Our current ability to modify the weather is dependent upon having the right types of clouds occurring naturally. Studies of clouds during drought versus non-drought periods typically indicate that the clouds during the two periods are quite similar. During drought periods, however, such clouds occur less frequently than in normal or wet periods. So while it may be possible to produce increases in precipitation of approximately 10% in dry, normal and wet periods the actual magnitude of accumulated seasonal increases from seeding would be reduced during drought periods. This fact has led some to state, perhaps justifiably, that “a 10% increase of nothing is nothing.” This attitude may be somewhat extreme, however, if the value of the water during drought periods is taken into account. Interestingly, there is a suggestion in one long-term program being conducted by North American Weather Consultants in central and southern Utah that the seeding increases expressed as a percentage may be higher in below normal winters. Mr. Larry Hjermstad, President of Western Weather

Consultants, suggests that this trend of higher percentage increases in below normal winters may also be indicated in his analysis of the San Juan Mountains seeding programs. It is probably safe to conclude that the “biggest bang for the buck” from cloud seeding programs will occur during normal to wet water years. The potential increases from very wet winter seasons may be truncated however due to seeding suspension criteria being invoked (e.g., high percent of normal snowpack, potential flood producing storms, etc.). One very significant advantage of the Colorado River system is the presence of impoundments that offer significant storage capacity (i.e. Flaming Gorge, Lake Powell and Lake Mead). Excess runoff produced through cloud seeding during wet years can almost always yield valuable carryover storage in these reservoirs.

As a consequence, routine application of weather modification technology year after year can help stabilize and bolster the water supplies in both surface and underground storage. Commitment to conduct a program each winter provides stability and acceptance by funding agencies and the general public. Programs can be designed so that they can be temporarily suspended or terminated during a given winter season should snowpack accumulate to the point where additional water may not be beneficial.

Other reasons to conduct programs in an ongoing fashion, rather than only during drier-than-normal winters, are that 1) it is very difficult to predict a wet or dry season in advance, 2) a season could start out wet but turn dry, resulting in missed seeding opportunities in the wet period, 3) drier seasons, by definition, will have fewer seeding opportunities, which means the total water increase due to seeding will be less, and 4) seeding in normal and above-normal water years will provide additional water supplies (surface and underground carryover) for use in dry periods.

13.0 METHODS OF EVALUATING THE EFFECTIVENESS OF OPERATIONAL CLOUD SEEDING PROGRAMS

The task of determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program for a particular season is rather difficult. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area and between one area and another during a given season. Since cloud seeding is normally feasible only when existing clouds are nearly (or already are) producing precipitation, it is hard to tell if, and how much, the precipitation was actually increased by seeding. The ability to detect a seeding effect becomes a function of the magnitude of the seeding increase and the number of seeded events, compared with the natural variability in the precipitation record. Larger seeding effects can be detected more easily and with a smaller number of seeded cases than are required to detect small increases. There are three basic methods of potentially detecting the effects of cloud seeding: 1) statistical approaches, 2) physical approaches, and 3) modeling approaches.

13.1 Statistical Approaches

Historically, the most significant seeding results have been observed in wintertime seeding programs in mountainous areas. However, the apparent differences due to seeding are relatively small relative to natural precipitation variability, being on the order of a 5-20 percent seasonal increase. In part, this accounts for the significant number of cases required to establish these results (often five years or more).

Despite the difficulties involved, some techniques are available for estimation of the effects of operational seeding programs. These techniques are not as rigorous or scientifically desirable as is the randomization technique used in research, where roughly half the sample of storm events is randomly left unseeded. The less rigorous techniques do, however, offer an indication of the long-term effects of seeding on operational programs.

A commonly employed technique is the "target" and "control" comparison. This technique is one described by Dr. Arnett Dennis in his book entitled “Weather Modification by Cloud Seeding (1980)”. This technique is based on the selection of a variable that would be affected by seeding (e.g., liquid precipitation, snowpack or streamflow). Records of the variable to be tested are acquired for an historical (not seeded) period of many years duration (20 years or more if possible). These records are partitioned into those located within the designated "target" area of the project and those in a nearby "control" area. Ideally the control sites should be selected in an area meteorologically similar to the target, but one that would be unaffected by the seeding (or seeding from other adjacent projects). The historical data (e.g., precipitation) in both the target and control areas are taken from past years that have not been subject to cloud seeding activities in either area. These data are evaluated for the same seasonal period as that of the proposed or previous seeding. The target and control sets of data for the unseeded seasons are used to develop an equation (typically a linear regression) that estimates the amount of target area precipitation, based on precipitation observed in the control area. This regression equation is then applied to the seeded period to estimate what the target area precipitation would have been without seeding, based on that observed in the control area(s). This allows a comparison between the predicted target area natural precipitation and that which actually occurred during the seeded period to determine if there are any differences potentially caused by cloud seeding activities. This target and control technique works well where a good historical correlation can be found between target and control area precipitation. Generally, the closer the target and control areas are in terms of elevation and topography, the higher the correlation will be. Control sites that are too close to the target area, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, a correlation coefficient (r) of 0.90 or better would be considered excellent. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set would be explained by the regression equation used to predict the variable (expected precipitation or snowpack) in the seeded years. An equation indicating perfect correlation would have an r value of 1.0.

13.2 **Physical Approaches**

The results from a statistical evaluation, such as a target/control analysis, can be strengthened through supporting physical studies, as recommended in a response to a National Research Council Report (2003) by the Weather Modification Association (WMA, 2004). One technique that has been employed by the Desert Research Institute (DRI) in the assessment of the effectiveness of at least the targeting (if not the magnitude) of seeding effects of winter programs is that of analyzing samples of snow from the target area during seeded periods to determine whether silver is present in projects that use silver iodide as the seeding agent (Warburton et al, 1995 and 1996). The following contains a summary of this technique.

Occasionally, samples of newly fallen snow are collected for an analysis of silver content. This is an evaluation technique encountered more frequently in research projects due to the expense involved. Snow samples collected prior to cloud seeding or from non-seeded storms are analyzed to establish the natural background silver content (if measurable with available analysis techniques) for comparison with snow samples taken from seeded storms. This technique is only valid for projects using silver iodide as the cloud seeding agent, although some analysis techniques are applicable to other possible cloud seeding agents as well (i.e., lead iodide). Several analysis techniques have been developed for use in such analyses, including neutron activation, proton excitation, and flameless atomic absorption. An example of an analysis of the downwind transport of silver iodide outside of primary target areas is given by (Warburton 1974). Warburton et al, 1996 demonstrates how trace chemical assessment techniques strengthen traditional target and control precipitation analyses.

A modification of this trace chemistry assessment technique involves the simultaneous release of a control aerosol along with an active seeding aerosol (Warburton et al. 1995). Such tracers have properties very similar to the seeding agent, with the key exception that they do not nucleate ice. Insoluble in water, they have an extremely low natural background in precipitation and are only removed from the atmosphere by passive precipitation scavenging mechanisms. Both the seeding agent and tracer are transported and scavenged in a very similar manner when conditions are not conducive for effective seeding. Given similar release rates, detecting the same concentrations of silver and the tracer, e.g., indium, in precipitation samples at downwind locations indicates that the two aerosols were most likely removed from the atmosphere solely by scavenging. On the other hand, when sufficient supercooled liquid water (SLW) exists and temperatures are cold enough for the active seeding material to nucleate new ice crystals, the ratio of silver to tracer in target area precipitation samples can be much greater than unity. This indicates that some fraction of the seeding material was directly responsible for the nucleation of ice crystals that eventually produced additional snowfall.

13.3 **Modeling Approaches**

Sophisticated atmospheric computer models have the potential to calculate the amounts of natural precipitation for short intervals (e.g., 6 hours, 12 hours) in mountainous areas. **If** these predictions are validated as accurate, they could be compared with the amount of precipitation that fell during seeded periods within the intended target area to determine the impact of seeding on target area precipitation. An attempt to verify the output of the RAMS computer model developed at Colorado State University versus observed and predicted modified precipitation due to cloud seeding was made for the 2003-2004 winter season in central Colorado, with rather mixed results. This work was done under the Colorado WDMP. Some of the conclusions from the final report (Colorado Water Conservation Board, 2005) are:

- When model simulated precipitation was compared to measured 24 hour precipitation at 61 SNOTEL sites the model exhibited a mean precipitation bias of 1.88.
- Comparison of model-predicted precipitation (control) versus seeded precipitation revealed that there was essentially no difference between the 86-day seed and control average totals.

The report listed the following possible reasons for the lack of differences between seed and control precipitation:

- The model-predicted seedability could be real; however, because of the model over prediction bias and low amounts of supercooled liquid water content, this possibility is doubtful.
- There is circumstantial evidence that the model-predicted supercooled liquid water content is too low, thereby underestimating seedability.
- A low-level warm temperature bias in the model results in delayed AgI nuclei activation and reduced effectiveness of the seeding agent in the model.

Wyoming is using a state-of-the art high resolution model known as WRF for guidance and evaluation of their five-year pilot project. It has not been demonstrated, even with this model, whether simulations are accurate enough to discern seeding effects from natural precipitation, or to even accurately predict the transport and dispersion of seeding material.

14.0 POTENTIAL INCREASES IN PRECIPITATION AND RUNOFF

Information provided in Sections 7, 9, 10 and 11 can be combined to provide estimates of potential increases in precipitation from existing and potential operational areas in the upper Colorado River Basin. **It is concluded that properly designed and conducted winter cloud seeding programs can increase the winter season precipitation in selected mountainous areas of the Upper and Lower Colorado River Basin in the range of 5 to 15%, with an average of 10%.**

Historical Studies

Earlier studies have been conducted of the potential for increases in precipitation and runoff in the Upper Colorado River Drainage. Some of the relevant studies are listed in Table 3, taken from Hunter et al, 2005.

Table 3. Previous water yield estimates from cloud seeding in the Colorado River Basin

Source	Dates	Water Yield (Acre-ft)
Bureau of Reclamation	1967-1968	1,870,000
Stanford Research Institute	1971-1972	1,150,000*
North American Weather Consultants (Twelve Basin Study)	1972-1973	1,315,000

* The original figure from the SRI document has been halved because it was based on an assumed 20% increase, whereas today the often accepted increase is 10%

It should be noted that the water yield provided in Table 3 for the Twelve Basin Study does not include the estimated increases from seeding the Gila River drainage in Arizona. The conservative estimated increases for this drainage were 154,000 acre feet. The Gila River is a tributary to the lower Colorado River.

A Recent Analysis by Steven Hunter, Bureau of Reclamation

A recent Reclamation report (Hunter et al, 2005) provided estimates of increases in April 1st snow water content due to cloud seeding in some of the areas considered in the earlier studies as documented in Table 3. Existing project target areas were used as is, which were defined with base thresholds at elevation contours of 7,000 feet MSL in Utah, and 8,000 to 9,000 feet MSL in Colorado and Wyoming. Figure 3 (see section 10) shows these locations as well as potential new target areas. Tables 1 and 2 (see section 10) provide geographical names associated with these areas.

Hunter et al, 2005 then used a new spatially distributed snow energy and mass balance model known as the Snow Data Assimilation System (SNODAS) with a 1 km (~ 0.6 mile) resolution to integrate the April 1st snow water content in the existing and potential cloud seeding target areas (Tables 1 and 2 provided in section 10) for the water years of 2004 and 2005. A longer period data base was not available using this SNODAS system.

Quoting from Hunter et al, 2005: "To estimate water volumes produced by seeding in *potential* areas, these integrations are divided by ten, since there is statistical, physical and modeling evidence for augmentation of natural precipitation (snowfall) by orographic cloud seeding of 10 percent." Physical cause-and-effect relationships have yet to be fully demonstrated, however. Since seeding has been conducted in *existing* areas, it is assumed that SNODAS SWE already reflects the 10% increase, or 110% of natural snowpack. Therefore the integrated SWE is divided by 11 in these areas. These calculations were made for both 2004 and 2005. While two years is hardly an extensive climatological record, it is fortuitous that the two years exhibited a large variation about the mean in precipitation amounts. That is, 2004 was an unusually dry year in the Upper Basin and 2005 was a relatively wet one."

Hunter et al, 2005 provide a rough approximation of potential increases in streamflow by using the additional amounts of snow water contents to estimate potential runoff. The authors mention the following caveat: "The reader is cautioned that water volumes resulting from increasing the existing April 1 snowpacks *do not necessarily equal runoff increases*. The latter increases may be changed by a given basin's hydrologic processes such as soil infiltration, antecedent soil moisture, slope and aspect, and vegetative cover. Other factors affecting a basin's precipitation-runoff relationship are spatial distribution of the snowpack, amount and timing of any rainfall on the pack, temperature, and evapotranspiration of snowmelt water." Table 4 (from Hunter, et al, 2005) lists the water volumes produced by 10% increases of the snowpack SWE on April 1 for both existing and potential target areas for the water years of 2004 and 2005. Hunter et al, 2005 indicates that these are conservative estimates, partly due to the more stringent selection criteria used to specify potential new target areas.

Table 4. Areas and water yields for 10% snowpack SWE increases from seeding, for existing (operational) seeding targets and potential new targets.

Existing Areas	**Area (km^2)**	**1 April 2004 Yield (ac-ft)**	**1 April 2005 Yield (ac-ft)**	**Mean Yield 04-05 (ac-ft)**
Utah	12,992	128,902	294,527	211,715
Colorado	17,767	240,852	499,190	370,021
Total	30,759	369,754	793,717	581,736
Potential Areas (All States) Total	13,611	217,890	352,978	285,434
Existing + Potential Areas Total	44,370	587,644	1,146,695	**867,170**

Estimates of Increases in Streamflow from the National Weather Service

National Weather Services River Forecast Center (RFC) personnel, whose offices are located in Salt Lake City, Utah, agreed to simulate the amounts of additional streamflow that might be generated by 0, 5, 10, and 15 % increases in October through March mean areal precipitation from the existing and potential new target areas. The output is the ensuing runoff (April through July) and base flow August through December. **As such, these numbers do not equate to annual runoff and are therefore somewhat conservative when compared to other studies that consider water year runoff.** RFC personnel used the Sacramento Soil Accounting Hydrologic Model and the Snow 17 model to provide these simulations. The 28 water years from 1975 through 2002 were used as the base period. Annual increases in streamflow were calculated and then averaged for the 0, 5, 10, and 15% increases in precipitation values. Output was provided for all the possible target areas (both existing and new areas) and separately for only the potential new areas. The RFC used the 8,000 foot MSL contour level to define the new target areas. The new areas included those identified by Hunter et al, 2005 in Colorado and Wyoming, plus the upper Colorado River drainage in the Rocky Mountain National Park area. Increases were calculated at various measurement points along the Colorado River and its tributaries with the end point being calculated unregulated (most diversions and reservoirs were accounted for) inflow to Lake Powell. Potential increases in streamflow were not calculated for the smaller potential target areas in southeastern Utah nor for the San Francisco Peaks, Mogollon Rim and White Mountain areas in Arizona.

Data from the River Forecast Center can be used to estimate the potential increases in streamflow in the upper Colorado River Basin due to cloud seeding. There are some difficulties in doing so that need to be recognized. One problem area is estimating the potential from "existing" cloud seeding program areas. The term "existing" might imply that seeding has been conducted continually in these areas throughout the 1975-2002 base period, but this is not the case. Seeding in these areas has been conducted for varying lengths of time. For example, seeding in the San Juan Mountains of southern Colorado began in 1970 and continued through 1986, then from 1996- present. Similarly, the seeded periods for a program over the Grand Mesa area of western Colorado are; 1975, 1979, 1990-1995 and 1999-present. For the Gunnison area of western Colorado, programs have been conducted from 2002 to the present. For a Denver Board of Water Commissioners program in the upper Colorado River Basin west of Denver, seeding was conducted from 2002 to 2004. The only program in Utah modeled by the River Forecast Center that would contribute to flows of the Colorado River would be the south slope of the Uinta Mountains program. This program has only been operated from 2002-present.

Another complication is that some of the seeding during these "seeded years" on some programs was conducted for only one or two months, not the entire winter season. **The point is that even though there has been some seeding in some areas of the upper Colorado River drainage during the base period, this seeding has not been conducted on an ongoing, systematic basis for long time periods. Since the River Forecast Center used a base period of 1975-2002 to provide average estimates of increases in streamflow, the question then becomes: would there be significant contributions to these streamflow averages due to the amount of cloud seeding that has actually been conducted?** It is beyond the scope of this study to quantify what the effects of seeding from these "existing" programs may have been during the historical base period of 1975-2002. **We estimated that the impact of the seeding during the historical period could be accounted for by applying a 5% reduction to the streamflow increases calculated by the River Forecast Center.** In reality, the 5% reduction probably overstates the magnitude of the seeding effects during the historical period.

Table 5 provides the resulting estimates of average increases in inflow to Lake Powell for both existing and new programs in the Upper Colorado River Basin, assuming full implementation in all areas, based on the historical base period of 1975-2002. The calculated increases are provided for 5, 10, and 15% increases in October through March precipitation. **The estimated average April through December increase in inflow to Lake Powell from a 10% increase in precipitation in existing and new areas located in the upper Basin States of Colorado, Utah and Wyoming would be 1,227,004 acre feet. The contributions to this total from the existing and new areas would be 576,504 and 650,500 acre feet, respectively.** April through December values were used since water year amounts were not available from the River Forecast Center.

Table 5 Estimated Average Increases in April through December Streamflow for Upper Basin States plus Arizona from Existing and New Programs for 5, 10, and 15% Increases in October through March Precipitation for the 1975-2002 Base Period (Acre Feet)

Seeded Area	5%	10%	15%
Existing	284,700	576,504	875,808
New	325,000	650,500	741,127
Arizona	+	154,000*	+
Totals	609,700	1,381,004	1,616,935

* Annual runoff amount based upon results from the earlier 12 Basin Study
\+ No estimate available

This discussion thus far has not addressed the potential increases in streamflow in the Colorado River that may result from new seeding activities in southeast Utah or Arizona (lower Colorado River Drainage). Recall that the analysis performed by the River Forecast Center excluded these areas. The earlier 12 Basin study mentioned in Table 3 (Elliott et al, 1973) contained an estimate of increases in streamflow from the Gila River drainage of Arizona associated with cloud seeding over the Mogollon Rim and White Mountains areas of Arizona. A conservative increase in average **annual** streamflow resulting from approximately a 10% increase in precipitation was 154,000 acre feet. No information is available regarding the possible impacts of cloud seeding in southeast Utah on streamflow. **The combined estimated average streamflow increases from seeding in the four states of Arizona, Colorado, Utah and Wyoming from both existing and new programs assuming a 10% increase in precipitation is 1,381,004 acre feet for the historical base period**. **Larger volumes of runoff would occur in above normal water years and smaller volumes in drier than normal water years**. It should be emphasized that this is an estimate of the total impact of seeding both existing and new areas without prior cloud seeding. Obviously there are some cloud seeding programs currently operating in some of the existing areas, so some of the potential additional streamflow is currently being realized. It is difficult to quantify what percentage of the potential from the existing areas is being realized. In fact this contribution may vary from year to year since some "existing" programs may be inactive one year but not the next. Also, a given program may only operate for two or three months, not the entire winter season.

The above should be considered a preliminary analysis; more detailed analyses are both warranted and recommended. It is encouraging, however, that the 1,381,004 acre foot value is in the range of the earlier, more comprehensive, studies mentioned in Table 3 which showed estimated increases ranging from 1,150,000 to 1,870,000 acre feet. These earlier studies have the added benefit that there were no cloud seeding programs being conducted in any of the potential target areas, so they avoided the complication that we now have of trying to remove the impacts of seeding in some areas during the historical base period used in this study. Certainly, if the recommendation that design studies be completed for each new program area is accepted, then a more focused streamflow evaluation could be conducted as part of this design work.

No attempt has been made in this analysis to differentiate between the impacts of modifications to existing programs versus the ways in which these areas are currently being seeded. Evaluations of some of the longer term programs in Utah suggest that 10% increases are being achieved. **Additional funding would therefore potentially raise the magnitude of the increases in the existing programs in Colorado and Utah beyond the 10% increases assumed in the above analysis. Could another 5% be achieved from modifications to existing programs? Perhaps this is possible. If so, the information in Table 5 could be used to provide estimates of what a 15% increase in precipitation might mean in terms of increases in streamflow above those resulting from 10% increases in precipitation.**

15.0 PRELIMINARY COST ESTIMATES

Some preliminary cost estimates are provided in two categories: 1) estimated costs to implement cloud seeding programs in the areas identified with good potential but without any current programs and 2) estimated costs of possible upgrades to existing programs. A few clarifications are needed.

- These are preliminary estimates and are subject to revision.
- Some of the improvements to existing programs may not be implemented but other upgrades may be suggested as alternatives by the clients or contractors of these programs which would change the cost estimates.
- Some of the new programs may not be implemented, again changing the cost estimates.
- Recommendations contained in section 18 propose that design studies be conducted for each potential new target area in order to customize cloud seeding activities to that area. As a consequence the scope of the programs and therefore their costs may change.
- Another recommendation in section 18 is that an evaluation component be built into the design of the new programs. These preliminary cost estimates include 15% of the estimated operating budget for new programs for evaluation purposes. Existing programs already have on-going evaluations built into their designs. As a consequence, no additional funds are proposed for evaluations of existing programs.
- Some of these preliminary cost estimates contain capitalization costs for equipment (e.g., remotely controlled ground generators). As a consequence, the operating costs of some programs could drop in future years.
- These figures do not include the costs of operating the existing programs in Colorado and Utah.
- These figures do not include the costs of operating a program over the west slopes of the Wind River Range in Wyoming since the Wyoming Water Development Commission has funded a five year program which includes this area.

Given the above caveats, the estimated first season costs of implementing the new programs and upgrading the existing programs are provided in Table 6.

Table 6 Estimated Program Costs

State	New Program Costs	Upgrades to Existing Programs	Total Costs
Arizona	$985,000	$0	$985,000
Colorado	$2,350,000	$1,475,000	$3,825,000
Utah	$1,050,000	$645,000	$1,695,000
Wyoming	$460,000	$0	$460,000
Total Cost	$4,845,000	$2,120,000	$6,965,000

Information from Table 6 can be compared to the total estimated additional streamflow that might be produced in the four states due to cloud seeding on an annual basis. Such a comparison indicates that the estimated cost of producing 1,381,004 acre feet would be $6,965,000. *This yields an estimated cost per acre foot of $5.04*.

16.0 POTENTIAL ENVIRONMENTAL IMPACTS

There have been a number of studies that examine the potential for the creation of negative environmental impacts associated with the conduct of winter cloud seeding programs. Several of these studies, which involved both office and field work, were supported by Reclamation offices in Denver under their "Project Skywater" program. Some of the relevant studies include:

- Potential Ecological Impacts of Snowpack Augmentation in the Uinta Mountains, Utah. A 1981 report from Brigham Young University authored by Kimball Harper (Harper, 1981) summarizing the results of a four year study.
- Ecological Impacts of Snowpack Augmentation in the San Juan Mountains, Colorado. A 1976 report edited by Harold Steinhoff (Colorado State University) and Jack Ives (University of Colorado) summarizing the results of a five year study (Steinhoff and Ives, 1976).
- The Medicine Bow Ecology Project. A 1975 report on studies conducted in the Medicine Bow Mountains of southern Wyoming (Knight, 1975).
- The Sierra Ecology Study. A five volume report summarizing work on possible impacts on the American River Drainage in California (Smith et al, 1980).

In general, these studies concluded that significant environmental effects due to the possible conduct of cloud seeding programs in these areas were not expected to occur. An example that supports this conclusion is as follows (from Steinoff and Ives, 1976):

"The results of the San Juan Ecology Project suggest that there should be no immediate, large-scale impacts on the terrestrial ecosystems of these mountains following an addition of up to 30 percent of the normal snowpack, but with no addition to maximum snowpacks. Further, much of the work reported here suggests that compensating mechanisms within the studies ecosystems are such that any impacts would be buffered, at least for short periods of time, and of lesser magnitude than the changes in snow conditions required to produce them."

Two topics are often voiced as ones of special concern: 1) the possibility of reducing precipitation downwind of potential target areas, and 2) the possible toxicity of seeding agents.

Downwind Effects

Perhaps the most frequently asked question regarding the establishment of a cloud seeding program in an area that has not been involved in previous cloud seeding programs is "Won't you be robbing Peter to pay Paul if you conduct a cloud seeding program in this area?". In other words, won't areas downwind of the intended target area experience less precipitation during the seeded periods? The rather surprising answer to this question is "no." This answer is based upon analysis of precipitation in areas downwind of research and operationally oriented cloud seeding programs. In a review paper on this topic, Long (2001) provides information from a variety of both winter and summer programs. One winter research program that is perhaps most relevant to winter time programs was one conducted by Colorado State University scientists in the Climax, Colorado area. This is a mountainous area located in the Central Colorado Rockies. This randomized seeding program was conducted in two phases that came to be known as Climax I and Climax II. Quoting from Long (2001), "Janssen, Meltsen and Grant (1974) investigated downwind effects of the Climax I and II projects. They noted that their investigation was post hoc and as such was exploratory rather than confirmatory. In order to detect downwind precipitation effects drifting from the Climax target area various time lags ranging from 3 to 187 hours of precipitation data from hourly stations in downwind locales were considered. Significant ratios of seeded to not-seeded precipitation, with low probabilities of being due to chance, were found downwind east and northeast of the Climax area. These ratios were in the range of 1.15 to 1.25 during the 3-12 hour time lag period." This suggests **increases** in precipitation on the order of 15-25% downwind of the intended target area. Long (2001) provides a summary statement in his paper as follows: "Downwind precipitation effects have been observed in geographic areas and time frames that are about the same magnitude as primary effects intended for the target area. There is little evidence of a decrease in precipitation outside the target area."

An example of an analysis of potential downwind effects from an operational winter program is found in Solak et al, 2003. This paper examined the precipitation that fell in areas located in eastern and southeastern Utah and western Colorado located downwind of a long-term winter program that has been conducted most winters since 1974 in the central and southern Wasatch Mountains of Utah. The abstract from this paper is as follows: "Estimations of effects on precipitation downwind of a long-standing operational snowpack augmentation project in Utah are made, using an adaptation of the historical target/control regression technique which has been used to estimate the seasonal effects over more than twenty seasons within the project's target area. Target area analyses of December-March high elevation precipitation data for this project indicate an overall season-average increase of about 14%. The downwind analyses indicate increases of similar magnitude to those for the target…extending to about 100 miles downwind."

Toxicity of Seeding Agents

By far the most common seeding agent in use today on winter orographic cloud seeding programs is silver iodide. The potential environmental impacts of silver iodide have been studied extensively. Klein (1978) in a book entitled “Environmental Impacts of Artificial Ice Nucleating Agents” concludes that “The major environmental concerns about nucleating agents (effects on plant growth, game animals, and fish, etc.) appear to represent negligible environmental hazards. The more subtle potential effects of silver-based nucleating agents, such as their possible ability to potentiate the movement or effects of other materials of environmental concern, or to influence the activity of microorganisms in soils and aquatic environments after being bioconcentrated by plants, warrant continued research and monitoring. Effects, if they occur, are not expected to involve unacceptable risks. The long-term use of silver iodide and the confidence which the weather modification profession has in delivery systems and in the efficacy of this material, make it unlikely that other agents, with the exception of dry ice, will be used on a large scale, unless there are improvements in delivery systems and major changes in the economics of silver availability.” In the same book a summary of potential impacts on humans is as follows: “The effects on humans of ingestion or topical contact with silver iodide used in cloud seeding can be considered negligible. Decade-long observations of cases (unrelated to cloud seeding) of ingestion of large silver doses revealed no physiological concern. In addition, surveys of seeding generator operators who have had long-term intensive contact with silver iodide reveal that they have not experienced medical difficulties.”

A report prepared by Tom Ryan (Ryan, 2005) of the Metropolitan Water District of Southern California contains the following summary on the topic of possible toxicity of silver iodide:

> *There has been a concern about the toxicity of the most common cloud seeding material, silver iodide (AgI) on the environment. The typical concentration of silver in rainwater or snow from a seeded cloud is less than 0.1 micrograms per liter. The Environmental Protection Agency recommends that the concentration of silver in drinking water not exceed 0.10 milligrams per liter of water. Many regions have much higher concentrations of silver in the soil than are found in seeded clouds. Industry emits 100 times as much silver into the atmosphere in many parts of the country, and silver from seeding is far exceeded by individual exposure from tooth fillings. The concentration of iodine in iodized salt used on food is far above the concentration found in rainwater from a seeded storm. No significant environmental effects have been noted around operational projects, many of which have been in operation for 30 to 40 years (WMA, 1996).*

The concentration of silver in rain water or snow from a seeded cloud using the above information is on the order of 1000 times less than the EPA Standard.

Seeding Suspensions

Almost all of today’s cloud seeding program designs identify situations in which seeding activities should be suspended. Examples of reasons for suspensions may include avalanche warnings, flash flood warnings, and excess snowpack accumulation. The last type of suspensions insures that cloud seeding does not result in snowpacks that exceed long-term historical maximum values. This factor was considered in the consideration of potential environmental impact studies such as that referenced in the Steinhoff study (1976).

17.0 POTENTIAL LEGAL ISSUES

There are certain licensing and permit requirements in each of the four states of Arizona, Colorado, Utah and Wyoming related pertaining to the conduct of weather modification (cloud seeding) programs. Some special consideration may need to be given to be needed for potential target areas that straddle state lines (e.g. the Sierra Madre/Park Range complex in northern Colorado and southern Wyoming). In these cases would permits be required from both states or could a joint permitting system be developed? Additional water generated from cloud seeding activities is typically treated as natural water that is appropriated according to the existing water rights in each area according to the regulations in these four states. There is a requirement to report cloud seeding activities to the National Oceanic and atmospheric Administration. Installation of ground-based equipment (e.g., remotely controlled silver iodide ground generators) on federal lands would require the issuance of special use permits and potentially the preparation of Environmental Assessments or Environmental Impact Statements. The preparation of such documents can be time consuming and costly.

18.0 CONCLUSIONS AND RECOMMENDATIONS

18.1 Conclusions

Cloud seeding over mountain areas in wintertime is an established technology. A large number of programs are conducted each winter throughout many parts of the world, including the western United States. Some of the United States programs, conducted in the Sierra Nevada Mountains of California, have been operated nearly continuously for periods of 40-55 years. There are a number of programs being conducted in Intermountain West drainages that are tributary to the upper Colorado River. Evaluations of research and operational programs indicate increases in precipitation in the range of 5-15% from well designed and executed programs. Capability statements from several professional societies indicate average increases in precipitation of 10% are reasonable. When a 10% increase in April 1st snow water content was applied to average snow water contents in the existing and potential new cloud seeding areas in the Upper Colorado River Basin, hydrologic modeling (conducted by the National Weather Service River Forecast Center in Salt Lake City) indicated that an **average** **1,227,004** additional acre feet of runoff may be added to upper Colorado River flows for the period of April through December. It is estimated an additional 154,000 acre feet of water could be produced by new seeding programs in Arizona amounting to a total of **1,381,004 acre feet. The estimated cost of producing this augmented streamflow is $6,965,000 or $5.04 per acre foot.** Larger volumes of runoff would occur in above normal water years and smaller volumes in drier than normal water years. No significant negative environmental effects are expected to be associated with these cloud seeding activities.

18.2 Recommendations

It is recommended that:

- New operational winter cloud seeding programs should be established in suitable areas in the states of Arizona, Colorado, Utah and Wyoming that are currently not part of active operational programs. This will enhance runoff into the Colorado River Basin. The term "operational" is used to denote programs whose primary goal is to produce additional precipitation. In other words, these programs would not be research oriented, although some research activities might be "piggybacked" on some of these programs should additional Federal or state funding become available. There is precedent for this approach in earlier "piggyback" research activities being added to operational programs in Colorado, Nevada and Utah through Federal funding.
- The development of new programs should follow the existing regulations that are concerned with weather modification activities within each State in which the program is to be conducted. All four states (Arizona, Colorado, Utah and Wyoming) have such regulations.
- Design studies should be conducted to guide the development of potential projects in new areas. Such studies will allow a customized approach to the development of each new program, taking into consideration area-specific factors such as climatology, topography, presence and frequency of seedable conditions, and seeding targeting and social considerations. The State of Wyoming, through their Water Resources Development Commission, has recently adopted this approach in their consideration of new programs in the Wind River, Sierra Madre, Medicine Bow, Salt and Wyoming Mountain Ranges.
- Existing operational programs within the Upper Colorado River Basin could be potentially enhanced. Means of enhancing these effects should be coordinated by the existing program sponsors and operators. Modifications might include additional seeding equipment, different types of seeding equipment (e.g. aircraft in addition to ground seeding and/or remotely controlled ground generators), and longer operational periods if the full seasonal window of seeding opportunity is not currently being seeded.
- Approximately 10-15% of the budget to conduct new programs should be devoted to evaluations of the effectiveness of the new programs. Two general types of evaluations should be considered; statistical (e.g. historical target/control analyses) and physical (e.g. chemical analysis of snow to detect the presence of silver associated with the release of the silver iodide seeding agent). Additional evaluations of existing programs are not proposed since the program sponsors and/or operators are currently performing their own evaluations.
- Additional simulations of impacts of assumed seeding increases on streamflow should be performed. Such simulation work should be a part of any design studies conducted for potential new seeding areas.
- It is recommended that a multi-year research program be conducted to determine the effectiveness of propane seeding in generating increases in precipitation over large scale areas the size of typical *operational* winter programs. It is recommended that the funding for this research program be obtained from federal sources and consequently the costs of conducting such a research program are not included in the cost estimates contained in Section 15.

- It is recommended that the Seven Basin States support any Congressional Bills that relate to the development of a "coordinated national weather modification research program" such as that proposed in HR 2995 and S 517.
- The Upper Basin States should develop cooperative agreements that feature the development of a "basin-wide water augmentation via cloud seeding program."
- Representatives of the Seven Basin States should consider convening an ad hoc committee to develop the scope of a short-term (3 year) program to augment and fund some of the existing operations and develop and fund some of the potential new programs.
- Representatives of the Seven Basin States should consider beginning discussions regarding cost-sharing and administration of new programs and augmentation of existing programs.

ACKNOWLEDGEMENTS

Tom Ryan of the Metropolitan Water District of Southern California and Steven Hunter of the Reclamation Denver offices agreed that portions of their reports could be used in the preparation of this paper. The cooperation of the Salt Lake City office of the National Weather Service, River Forecast Center in performing analyses of the impacts of predicted increases in precipitation upon runoff was extremely useful. Several people provided reviews and comments on a draft of this paper including: Don Ostler (Upper Colorado River Commission), Todd Adams (Utah, Division of Water Resources), Joe Busto (Colorado Water Conservation Board), and Tom Ryan (Metropolitan Water District of Southern California).

Cover Photo by David Yorty, North American Weather Consultants

REFERENCES

ASCE, 1995: Guidelines for Cloud Seeding Augment Precipitation. ASCE Manuals and Reports on Engineering Practice No. 81.

ASCE, 2004: Standard Practice for the Design and Operation of Precipitation Enhancement Projects. ASCE/EWRI Standard 42-04, Reston, Virginia, 63 pp.

California Department of Water Resources, 2005: California Water Plan Update 2005 Volume 2-Resource Management Strategies, Chapter 14, Precipitation Enhancement.

Cooper, W. A., and P. Lawson, 1984: Physical interpretation of results from the HIPEX-1 experiment. AMS *Journal of Climate and Applied Meteorology,* **23**, p 523-540.

Dennis, A.S., 1980: Weather Modification by Cloud seeding. Academic Press, New York, NY, 267 pp.

Elliott, R.D., J.F. Hannaford, and R.W. Schaffer, 1973: Twelve Basin Investigation; Analysis of Potential Increases in Precipitation and Streamflow Resulting from Modification of Cold Orographic Clouds in Selected River Basins of the western United States. North American Weather Consultants Report No. 15-18 to the Bureau of Reclamation.

Elliott, R.D., R.W. Schaffer, A.C. Court and J.F. Hannaford, 1976: Colorado River Basin pilot Project; Comprehensive Evaluation Report. Aerometric Research Report No. ARI-76-1 to Bureau of Reclamation.

Gagin, A., and J. Neumann, 1981: The second Israeli randomized cloud seeding experiment: evaluation of the results. AMS *Journal of Applied Meteorology*, **20**, p. 1301-1311.

Grant, L.O. and R. D. Elliott, 1974: The cloud seeding temperature window. AMS *Journal of Applied Meteorology*, **13**, p. 355-363.

Grant, L., 1986: Hypotheses for the Climax wintertime orographic cloud seeding experiments. *Precipitation Enhancement – A Scientific Challenge, Meteorlogical. Monograph.*, No. **43**, American Meteorological Society, 105-108.

Griffith, D.A., J.R. Thompson and R.W. Shaffer, 1983: Winter orographic cloud seeding northeast of Bear Lake, Utah. WMA *Journal of Weather Modification*. **15**, p.23-27.

Griffith, D.A., 1993: Planting the Seeds for Increased Water Availability for Hydro. *Hydro Review*, p.122-128.

Griffith, D. A., J. R. Thompson and D. A. Risch, 1991: A Winter Cloud Seeding Program in Utah. WMA *Journal of Weather Modification*, **23**, p. 27-34.

Griffith, D. A., J. R. Thompson, D. A. Risch, and M. E. Solak, 1997: An update on a winter cloud seeding program in Utah. WMA *Journal of Weather Modification*, **29**, p. 95-99.

Griffith, D.A. and M.E. Solak, 2002: Economic Feasibility Assessment of Winter Cloud Seeding in the Boise River Drainage, Idaho. WMA, *Journal of Weather Modification*, **34**, p. 39-46.

Griffith, D.A., D.P. Yorty and M.E. Solak, 2004: The Development, Conduct and Evaluation of a Cloud Seeding Program for the Gunnison River Basin, Colorado during the 2003-2004 Winter season. North American Weather Consultants Report No. WM 04-3 to Gunnison County.

Griffith, D.A., D.P. Yorty and M.E. Solak, 2005: The Conduct and Evaluation of a Cloud Seeding Program for the Gunnison River Basin, Colorado during the 2004-2005 Winter season. North American Weather Consultants Report No. WM 05-2 to Gunnison County.

Griffith, D.A., M.E. Solak and D.P. Yorty, 2005: Summary and Evaluation of the Winter 2004-2005 Cloud seeding Program in the Boise River Drainage. North American Weather Consultants Report No. WM 05-3 to Boise Project Board of Control.

Harper, K.T., 1981: Potential Ecological Impacts of Snowpack Augmentation in the Uinta Mountains, Utah. Brigham Young University Report to the Utah Division of water Resources, 291p.

Henderson, T.J., 2003: New Assessment of the Economic Impacts from Six Winter Snowpack Augmentation Projects. WMA, *Journal of Weather Modification*, **35**, p. 41-44.

Hill, G.E., 1980: Seeding opportunity recognition in winter orographic clouds. AMS *Journal of Applied Meteorology*, **19**, p. 1371-1381.

Hjermstad, L., 2001: An Analysis of Regional SNOTEL and Ski Area Precipitation Data to Evaluate Precipitation Changes Resulting from Ten Seasons of Wintertime Cloud Seeding Operations over the Vail Ski Area. Western Weather Consultants report to Vail Ski Area, 28p.

Hunter, S.M., S. Meyer and R. Aman, 2005: Water Augmentation from Cloud Seeding in the Colorado River Basin. Bureau of Reclamation Technical Service Center, 9p.

Idaho Power, 2005: 2005 Update on Idaho Power Company's Weather Modification Project on the Upper Payette River Basin.

Klein, D.A., 1978: Environmental Impacts of Artificial Ice Nucleating Agents. Dowden, Hutchinson & Ross, Inc., Stroudsburg, Pennsylvania.

Knight, D. H., Anderson, A. D., Baxter, G. T., Diem, K. L., Parker, M., Rechard, P. A., Singleton, P. C., Thilenius, J. F., Ward, A. L., and Weeks, R. W. (1975). "The Medicine Bow Ecology Project." *Final Report to Bureau of Reclamation*, University of Wyoming, Laramie, WY.

Long, A. B., 2001: Review of Downwind Extra-Area Effects of Precipitation Enhancement. WMA *Journal of Weather Modification*, **33**, p. 24-45.

Mielke, P.W. et al, 1971: An independent replication of the Climax wintertime orographic cloud seeding experiment. AMS *Journal of Applied Meteorology*, **10**, p.1198-1212.

Mielke, P.W., G.W. Brier, L.O. grant, G.J. Mulvey, and P.N. Rosenzweig, 1981: A statistical reanalysis of the replicated Climax I & II wintertime orographic cloud seeding experiments. AMS *Journal of Applied Meteorology*, **20**, p. 643-659.

National Research Council of the National Academies of Science. Critical Issues in Weather Modification Research. The National Academies Press, Washington, D.C., 2003.

Orville, H.D., B.A. Boe, G.W. Bomar, W.R. Cotton, B. L. Marler, and J.A. Warburton, 2004: A Response by the Weather Modification Association to a National Research Council Report. Weather Modification Association, 52p.

Rangno, A.L. and P.V. Hobbs, 1987: Reevaluation of the Climax cloud seeding experiments using NOAA published data. AMS *Journal of Climate and Applied Meteorology*, **26**, p.757-762.

Rangno, A.L. and P.V. Hobbs, 1993: Further analyses of the Climax cloud seeding experiments. AMS *Journal of Applied Meteorology*, **32**, p. 1837-1847.

Rauber, R.M., L.O. Grant, D. Feng and J.B. Snider, 1986: The characteristics and distribution of cloud water over the mountains of northern Colorado during wintertime storms. Part I: temporal variations. AMS *Journal of Climate and Applied Meteorology*, **25**, p. 469-488.

Reynolds, D. W., 1988: A Report on Winter Snowpack-Augmentation. *Bulletin of the American Meteorological Society*, **69**, p.1290-1300.

Reynolds, D.W., 1991: Design and Testing of a Remote Ground-Based Liquid Propane Dispenser. WMA *Journal of Weather Modification*, **23**, p. 49-53.

Reynolds, D.W., 1991: Design and Testing of a Remote Ground-Based Liquid Propane Dispenser. WMA *Journal of Weather Modification*, **23**, p. 49-53.

Reynolds, D.W., 1992: A Snowpack Augmentation Program Using Liquid Propane. Preprints *Symposium on Planned and Inadvertent Weather Modification,* American Meteorological Society, Jan. 5-10, Atlanta, GA, p. 88-95.

Ryan, T., 2005: Weather Modification for Precipitation Augmentation and its Potential Usefulness to the Colorado River Basin States. Metropolitan Water District of Southern California Report, 34p.

Solak, M.E., D.P. Yorty and D.A. Griffith, 2003: Estimations of Downwind Cloud Seeding Effects in Utah. WMA *Journal of Weather Modification*, **35**, p. 52-58.

Solak, M.E., D.P. Yorty and D.A. Griffith, 2003: Target/Control Evaluation of the Denver Board of Water Commissioners Winter Snowpack Enhancement Project, 2002-2003. NAWC Report No. WM 03-2 to the Denver Board of Water Commissioners.

Stauffer, N.E., Jr., 2001: Cloud Seeding – The Utah Experience. WMA *Journal of Weather Modification*, **33**, p. 70-73.

Steinhoff and Ives, 1976: Ecological Impacts of Snowpack Augmentation in the San Juan Mountains of Colorado, Final Report of the San Juan Ecology Project to the Bureau of Reclamation from Colorado State University, Contract No. 14-06-D-7052, 489pp.

Super, A.B. and J.A. Heimbach, Jr., 1983: Evaluation of the Bridger Range Winter Cloud Seeding Experiment Using Control Gages. AMS *Journal of Applied Meteorology,* **22**, p. 1989-2011.

Super, A.B., E.W. Holroyd and J.T. McPartland, 1989: Winter Cloud Seeding Potential on the Mogollon Rim. Bureau of Reclamation Technical Report No. R-89-02, 173p.

Super, A. B., 1990: Winter orographic cloud seeding status in the intermountain-West. WMA, *Journal of Weather Modification*, **22**, p. 106-116.

Super, A.B. and A.W. Huggins, 1992: Investigations of the targeting of ground-released silver iodide nuclei in Utah – Part I: Ground observations of silver in snow and ice nuclei. WMA *Journal of Weather Modification*, **24**, p. 19-34.

Super, A.S., J.C. Lease and J.T. McPartland, 1993: Validation of Precipitation Management by Seeding Winter Orographic Clouds in the Colorado River Basin. Bureau of Reclamation, Water Augmentation Group, Denver, Colorado, 160pp.

Super, A. B. and E. W. Holroyd, 1997: Some physical evidence of AgI and liquid propane seeding effects on Utah's Wasatch plateau. WMA *Journal of Weather Modification*, **29,** 8-32.

Super, A. B., 1999. "Summary of the NOAA/Utah Atmospheric Modification Program: 1990-1998." WMA *Journal of Weather Modification*, **31**, p. 51-75.

Super, A.B. and J.A. Heimbach, 2005: Final report on Utah cloud seeding experimentation using propane during the 2003-04 winter. Report to Utah Dept. of Natural Resources, Salt Lake City, Utah, 114 pp.

Warburton, J.A., 1974: Physical Evidence of Transport of Cloud Seeding Materials Into Areas Outside Primary Targets. AMS Proceedings, *International Conference on Weather Modification*, Boston, MA, p.185-190.

Warburton, J. A., R. H. Stone and B. L. Marler, 1995a: How the transport and dispersion of AgI aerosols may affect detectability of seeding effects by statistical methods. AMS *Journal of Applied Meteorology*, **34**, p.1930-1941.

Warburton, J. A., L. G. Young and R. H. Stone, 1995b: Assessment of seeding effects in snowpack augmentation programs: ice nucleation and scavenging of seeding aerosols. AMS *Journal of Applied Meteorology*, **34**, 121-130.

Warburton, J.A., S.K. Chai, R.H. Stone and L.G. Young, 1996: The Assessment of Snowpack Enhancement by Silver Iodide Cloud Seeding using the Physics and Chemistry of the Snowfall. WMA *Journal of Weather Modification*, **28**, p.19-28.

Weisbecker, L.W., 1974: The Impacts of Snow Enhancement; A Technology Assessment of Winter Orographic Snowpack Augmentation in the Upper Colorado River Basin. Stanford Research Institute, University of Oklahoma Press, Norman, Oklahoma.

WMI, 2005: Wyoming Level II Weather Modification Feasibility Study. Final Report to Wyoming Water Development Commission, 151pp.

APPENDIX A

EXCERPTS FROM CAPABILITY STATEMENTS REGARDING WINTER PROGRAMS

<u>Weather Modification Association</u> (2005*)*

"Winter Precipitation Augmentation

The capability to increase precipitation from wintertime orographic cloud systems has now been demonstrated successfully in numerous "links in the chain" research experiments. The evolution, growth and fallout of seeding-induced (and enhanced) ice particles have been documented in several mountainous regions of the western U. S. Enhanced precipitation rates in seeded cloud regions have been measured in the range of hundredths to >1 mm per hour. Although conducted over smaller temporal and spatial scales, research results tend to be consistent with evaluations of randomized experiments and a substantial and growing number of operational programs where 5% - 15% increases in seasonal precipitation have been consistently reported. Similar results have been found in both continental and coastal regions, with the potential for enhanced precipitation in coastal regions appearing to be greater in convective cloud regimes. The consistent range of indicated effects in many regions suggests fairly widespread transferability of the estimated results.

Technological advances have aided winter precipitation augmentation programs. Fast-acting silver iodide ice nuclei, with higher activity at warmer temperatures, have increased the capability to augment precipitation in shallow orographic cloud systems. Numerical modeling has improved the understanding of atmospheric transport processes and allowed simulation of the meteorological and microphysical processes involved in cloud seeding. Improvements in computer and communications systems have resulted in a steady improvement in remotely controlled cloud (ice) nuclei generators (CNG's), which permit improved placement of CNG's in remote mountainous locations.

Wintertime snowfall augmentation programs can use a combination of aircraft and ground-based dispersing systems. Although silver iodide compounds are still the most commonly used glaciogenic (causing the formation of ice) seeding agents, dry ice is used in some warmer (but still supercooled) cloud situations. Liquid propane also shows some promise as a seeding agent when dispensers can be positioned above the freezing level on the upwind slopes of mountains at locations adequately far upwind to allow growth and fallout of precipitation within the intended target areas. Dry ice and liquid propane expand the window of opportunity for seeding over that of silver iodide, since they can produce ice particles at temperatures as warm as -0.5^o C. For effective precipitation augmentation, seeding methods and guidelines need to be adapted to regional meteorological and topographical situations.

Although traditional statistical methods continue to be used to evaluate both randomized and non-randomized wintertime precipitation augmentation programs, the results of similar programs are also being pooled objectively in order to obtain more robust estimates of seeding *efficacy. Objective evaluations of non-randomized operational programs continue to be a difficult challenge. Some new methods of evaluation using the trace chemical and physical properties of segmented snow profiles show considerable promise as possible means of quantifying precipitation augmentation over basin-sized target areas."*

American Meteorological Society **(1998)**

"Precipitation Increase

There is statistical evidence that precipitation from supercooled orographic clouds (clouds that develop over mountains) has been seasonally increased by about 10%. The physical cause-and-effect relationships, however, have not been fully documented. Nevertheless, the potential for such increases is supported by field measurements and numerical model simulations"

World Meteorological Organization **(2004)**

"Precipitation (Rain and Snow) Enhancement

This section deals with those precipitation enhancement techniques that have a scientific basis and that have been the subjects of research. Other non-scientific and unproven techniques that are presented from time to time should be treated with the required suspicion and caution.

Orographic mixed-phase cloud systems

In our present state of knowledge, it is considered that the glaciogenic seeding of clouds formed by air flowing over mountains offers the best prospects for increasing precipitation in an economically-viable manner. These types of clouds attracted great interest in their modification because of their potential in terms of water management, i.e. the possibility of storing water in reservoirs or in the snowpack at higher elevations. There is statistical evidence that, under certain conditions, precipitation from supercooled orographic clouds can be increased with existing techniques. Statistical analyses of surface precipitation records from some long-term projects indicate that seasonal increases have been realized.

Physical studies using new observational tools and supported by numerical modeling indicate that supercooled liquid water exists in amounts sufficient to produce the observed precipitation increases and could be tapped if proper seeding technologies were applied. The processes culminating in increased precipitation have also been directly observed during seeding experiments conducted over limited spatial and temporal domains. While such observations further support the results of statistical analyses, they have, to date, been of limited scope. The cause and effect relationships have not been fully documented, and thus the economic impact of the increases cannot be assessed.

This does not imply that the problem of precipitation enhancement in such situations is solved. Much work remains to be done to strengthen the results and produce stronger statistical and physical evidence that the increases occurred over the target area and over a prolonged *period of time, as well as to search for the existence of any extra-area effects. Existing methods should be improved in the identification of seeding opportunities and the times and situations in which it is not advisable to seed, thus optimizing the technique and quantifying the result.*

Also, it should be recognized that the successful conduct of an experiment or operation is a difficult task that requires scientists and operational personnel. It is difficult and expensive to fly aircraft safely in supercooled regions of clouds. It is also difficult to target the seeding agent from ground generators or from broad-scale seeding by aircraft upwind of an orographic cloud system."