WEATHER MODIFICATION FEASIBILITY STUDY FOR UPPER BOISE RIVER BASIN, IDAHO

Prepared for

Idaho Water Resource Board

by

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David P. Yorty

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Report No. WM 09-12
Project No. 09-246

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1.0 INTRODUCTION

A brief background on the events that led to this Boise River feasibility study is provided in the following. North American Weather Consultants, Inc. (NAWC) received a Request for Proposals entitled “Consultant Services for the Upper Snake River Basin Weather Modification Feasibility Study.” This RFP was issued by the Idaho Water Resource Board (IWRB) in July 2007. NAWC responded to this RFP with a formal proposal (NAWC # 07-209), which was due September 4, 2007. NAWC was notified on October 26, 2007 that it had been selected to perform this work. A contract to conduct the work was finalized on January 8, 2008.

NAWC completed this study in October 2008 (Griffith, et al, 2008). NAWC received queries from the IWRB following the completion of this study about extending the type of analyses developed in the Eastern Snake study to the Big and Little Wood River Basins located in central Idaho. An agreement was reached on May 5, 2009 between the IWRB and NAWC for the performance of this supplemental study. This study was completed in August (Griffith and Yorty, 2009). Prior to the completion of this report IWRB personnel asked if NAWC could perform a feasibility/design study for the Upper Boise River Basin. An agreement between the IWRB and NAWC was reached on July 9, 2009 in which NAWC was tasked to perform this study. An interesting aspect of this study is that NAWC has been conducting an operational cloud seeding program in the Upper Boise River Basin for some winter seasons that dates back to the 1992-1993 winter season.

Seven tasks were identified that NAWC would perform in the completion of this study:

1. Review and Analysis of the Climatology of the Target Area.
2. Review and Assessment of the Existing program.
3. Evaluate Enhancements to the Existing Program.
4. Establish Criteria for Program Operation.
5. Development of Monitoring and Evaluation Methodology.
6. Operation Suspension Criteria
7. Preparation of a Final Report including an Executive Summary.

The contract also stipulated that two sections of the earlier NAWC report prepared for the Eastern Snake River Basin be included in this study. These sections were: 1) Review and Summary of Prior Studies and Research, and 2) Review of Environmental and Legal Aspects. These sections are provided as Appendices A and B to this report.

The following sections of this report describe the work that NAWC conducted in completing the above tasks. We will use the abbreviation UBRB to refer to this Upper Boise River Basin program.

2.0 GENERAL DESCRIPTION OF THE PROPOSED TARGET AREA

The Idaho Water Resources Board (IDWR) specified the area of interest to be the Upper Boise River Basin (UBRB). This area lies within portions of Boise, Camas and Elmore Counties. The IDWR noted that the upper Boise, including the North Middle and South Forks, and Mores Creek supplies 90% of the water for the lower Boise Basin. The UBRB ranges in elevation from approximately 3,000 feet MSL at Lucky Peak Dam to crest elevations of approximately 8,500 to 9,500 feet MSL between the Boise River and Big Wood River Basins. There are isolated peaks in the area over 10,000 feet MSL (e.g., Snowyside Peak, 10,651 feet MSL). Figure 2.1 provides a map of the area that includes the locations of three major reservoirs, two on the Middle Fork (Arrowrock and Lucky Peak) and one on the South Fork (Anderson Ranch).

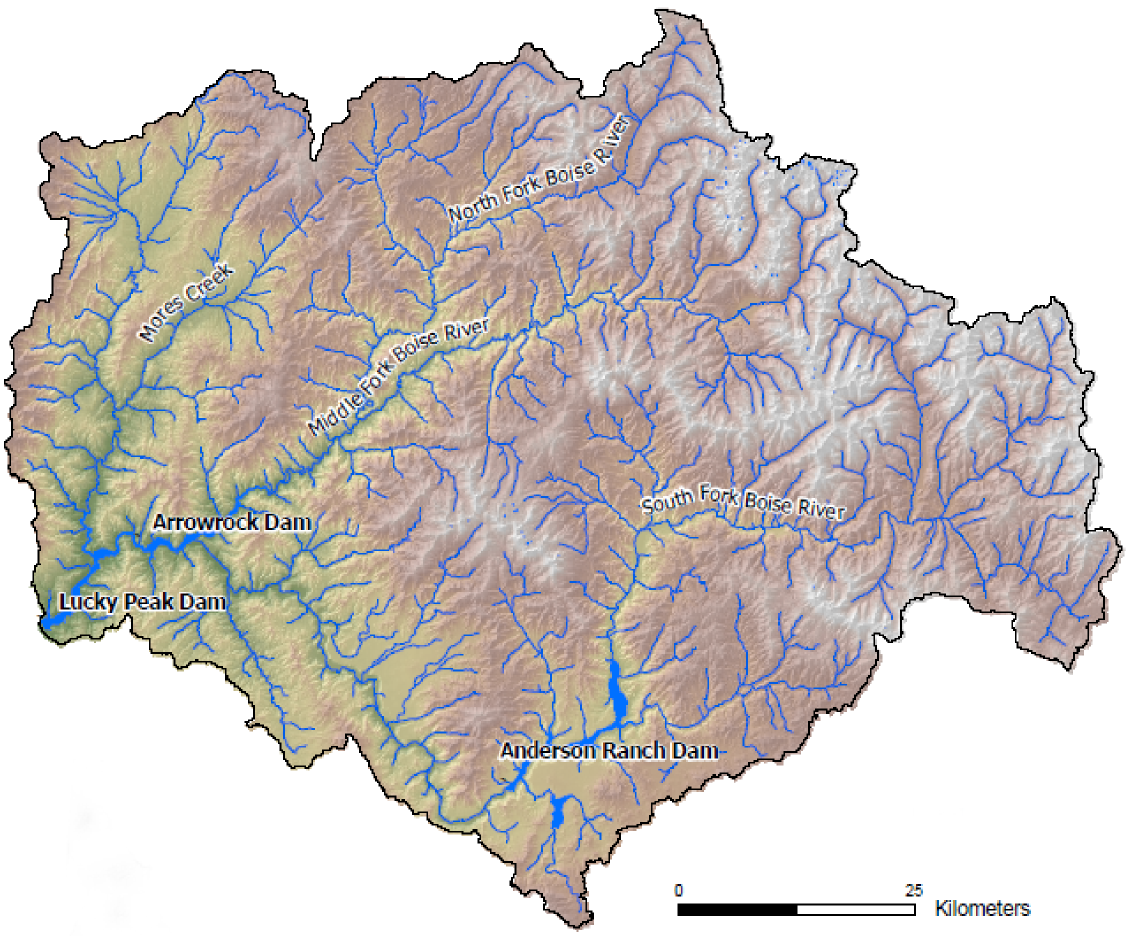

Figure 2.1 The Boise River Basin above Lucky Peak Dam

Figure 2.2 provides a map that contains a straight-line route from Lucky Peak Dam to Ketchum, Idaho. Figure 2.3 provides the vertical profile along this line. Figure 2.3 demonstrates that the UBRB is comprised of significant intermediate elevations in the range of 5,000 to 6,500 feet MSL. As a consequence, NAWC recommends that the intended target area for the UBRB program be defined as those regions in the basin that are above 5,000 feet MSL. This area is outlined on Figure 2.4.

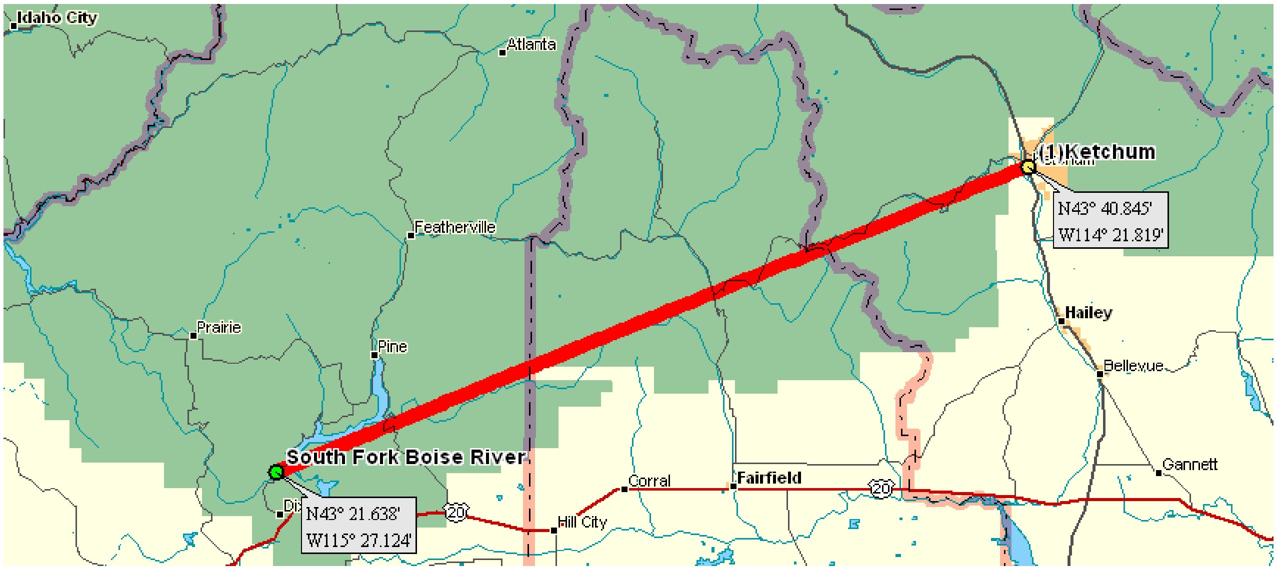

Figure 2.2 Location of Cross-section shown in Figure 2.3

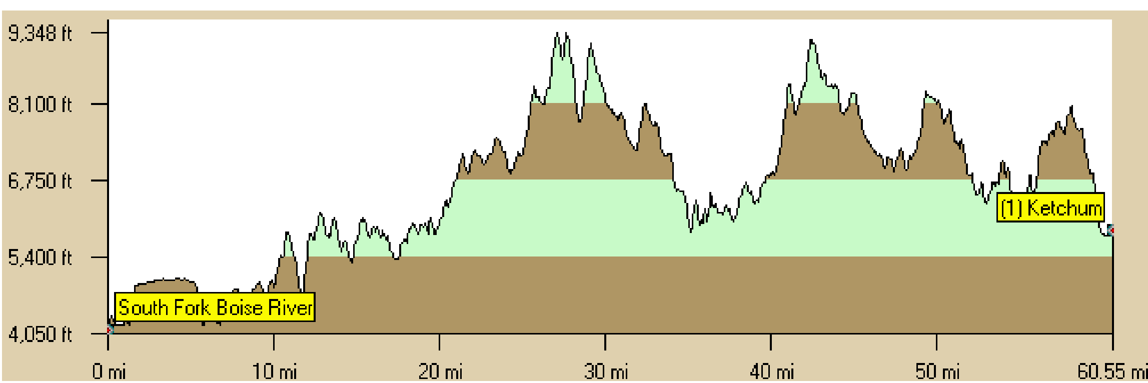

Figure 2.3 Cross-section Showing Elevation Profile, Lucky Peak Dam to Ketchum, Idaho

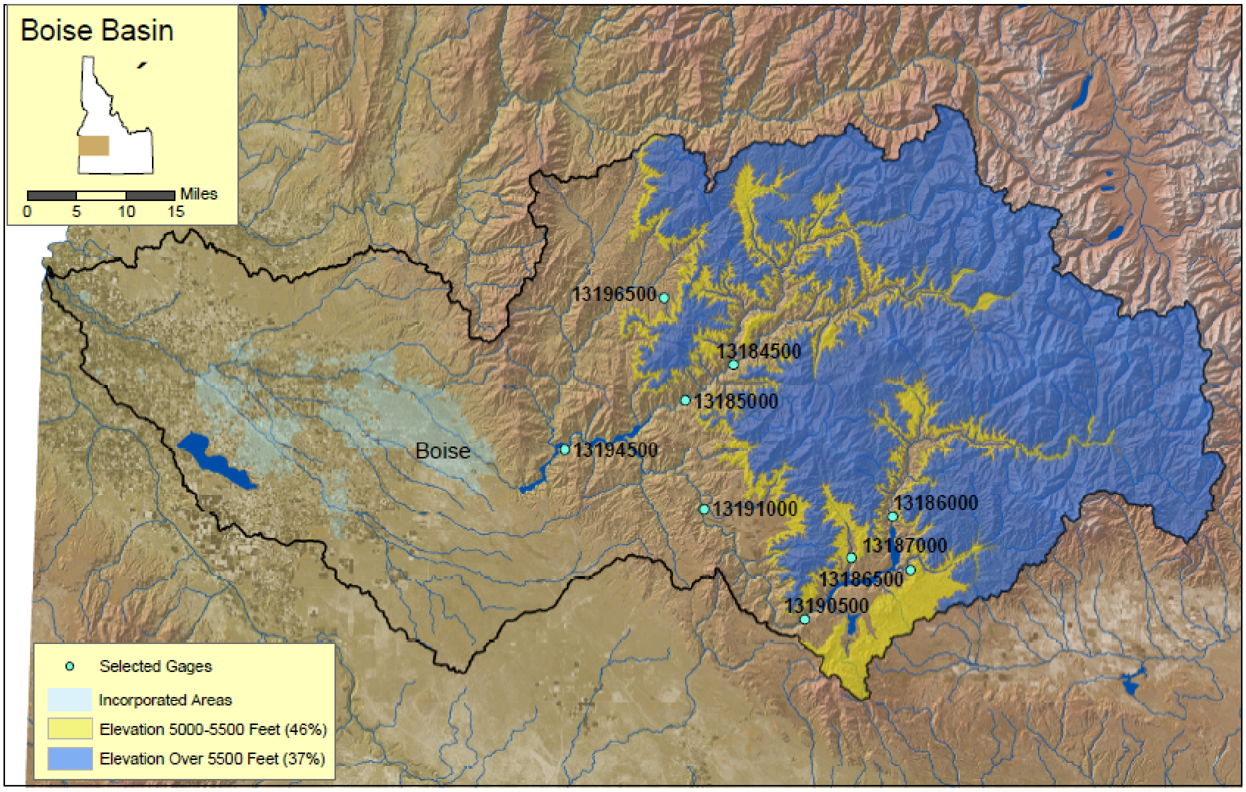

Figure 2.4 Proposed Target Area above 5000 Feet (area includes those areas outlined in yellow and blue)

3.0 CLOUD SEEDING CONCEPTS AND GENERAL PROGRAM DESIGN CONSIDERATIONS

3.1 Brief Description of the Theory of Cloud Seeding for Precipitation Augmentation

A basic summary of the concept of how cloud seeding is thought to work in wintertime mountainous (orographic) settings is worthwhile at this juncture in order to set the stage for the development of a preliminary design for the proposed program area. 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 said to be in a "supercooled" state. Thus the phrase supercooled liquid water (SLW) has been coined to refer to the presence of such water droplets in a cloud. In fact, pure water droplets in a laboratory setting have been observed to remain unfrozen to a temperature of -38.2^0 F (-39^0 C). Droplets at -40^0 F (-40^0 C) freeze spontaneously through a process known as homogeneous nucleation. In order for water droplets to freeze at temperatures between 30.2^0 F (-1^0 C) and -38.2^0 F (-39^0 C) they must come in contact with foreign particles 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 composed of tiny soil particles or dead bacteria (e.g., pseudomonas syringe). Numerous observations around the world have indicated that the numbers of naturally occurring freezing nuclei that can cause heterogeneous nucleation to occur are temperature dependent. These nuclei become increasingly active with decreasing temperatures. Once a supercooled water droplet is frozen, creating an ice crystal, it will grow through vapor deposition (and possibly aggregation) from the water droplets surrounding it and, given the right conditions, form a snowflake large enough to fall from the cloud and reach the ground. **Supercooled water droplets are the targets of opportunity in order to increase precipitation through cloud seeding.**

Studies of both orographic and convective clouds have suggested that clouds colder than ~ -13^0 F (-25^0 C) have sufficiently large concentrations of natural ice crystals such that seeding can either have no effect or possibly even reduce precipitation (Grant and Elliott, 1974; Grant, 1986; Gagin and Neumann, 1981; Gagin et al., 1985). It is possible that seeding such cold clouds could reduce precipitation by creating so many ice crystals that they compete for the fixed supply of water vapor and result in numerous, slowly settling ice crystals which sublimate before reaching the ground. 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 a) the low efficiency of ice crystal production by silver iodide at temperatures greater than 24.8^0 F (-4^0 C) and b) 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 (-5^0 C) to -13^0 F (-25^0 C) where clouds respond favorably to silver iodide seeding (i.e., exhibit seedability). Dry ice (frozen carbon dioxide) seeding via aircraft extends this temperature window to temperatures just below 32^0 F (0^0 C), but the slow rates of ice crystal vapor deposition growth are a factor at this warm end of the temperature spectrum.

Orographic clouds in the mountainous western states are associated with passing storm systems. Wind flow over a mountain barrier causes the orographic lift to produce or enhance the cloud. Other types of clouds associated with frontal boundaries, convergence bands, and convective instability are also present during these storm systems, thus the orographic cloud scenario is often complicated by the dynamics of the storm system (changing winds, temperatures, and moisture). *In situ* and remote observations of SLW in orographic clouds (e.g., 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 only reaching to approximately or slightly above the height of the mountain barrier). Figure 3.1 provides a stylized depiction of this SLW zone associated with a mountain barrier. NAWC developed this figure based upon the results from a number of winter research programs that have used microwave radiometers and aircraft to document the presence of

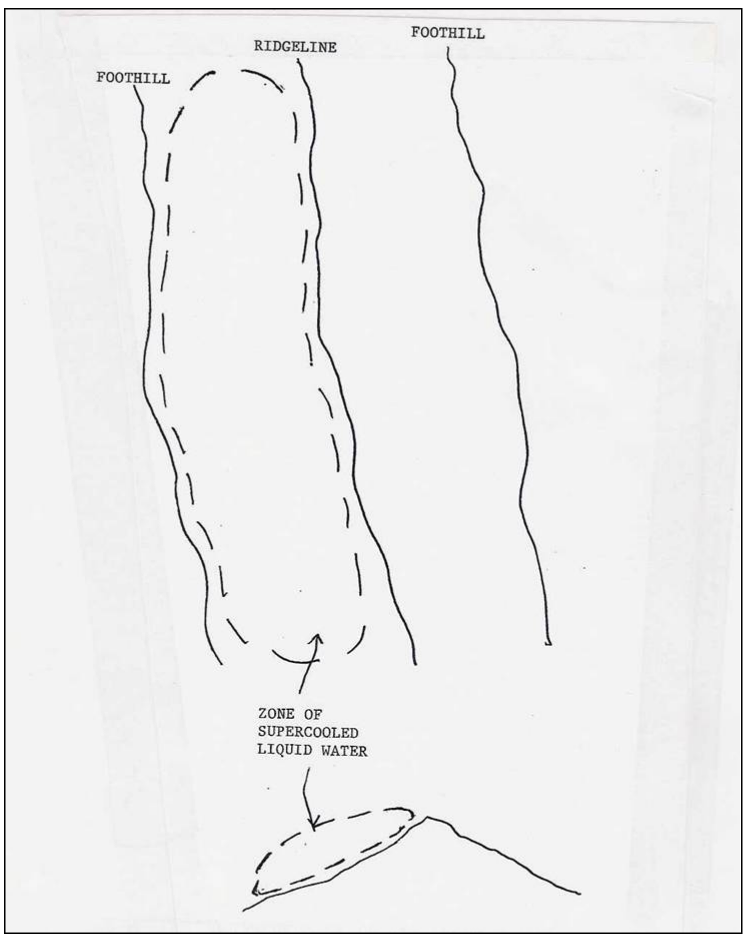

Figure 3.1 Depiction of Supercooled Liquid Water Zone

the SLW. Super, 1990, reporting on measurements of SLW observed in winter research programs in the western U.S. states, “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 series of quotes from Super, 1990 are as follows: “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 data from 57 vibrating wire sondes released 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.” Research conducted in the Sierra Nevada Mountains of California as summarized by Reynolds (1988) indicate that shallow orographic clouds are considered the best candidates for winter snowpack augmentation, similar to the findings found in the above references.

The basic consideration in the development of the design of a winter orographic cloud seeding program is to develop a seeding methodology that will tap this reservoir of SLW to convert cloud 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 terms of producing precipitation that reaches the ground.

If SLW clouds upwind and over mountain barriers are routinely “seeded” to produce appropriate concentrations of ice crystals, exceeding 1 to 10 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 and SLW at warmer cloud temperatures will produce snowfall when natural snowfall rates are negligible. Seeded snowfall rates are usually light, on the order of .04"/hr (1 mm/hr) or less of water equivalent, consistent with median natural snowfall rates in the Intermountain West (Super and Holroyd, 1999).

3.2 General Program Design Considerations

There are a number of factors to be considered in the development of a design for a cloud seeding program. The American Society of Civil Engineers published a Standard entitled “Standard Practice for the Design and Operation of Precipitation Enhancement Programs” in 2004 (ASCE, 2004). This Standard lists the following as factors that should be considered:

1) Definition of program scope
2) Seeding agent selection
3) Targeting and delivery methods
4) Meteorological data collection and instrumentation

5) Selection and siting of equipment
6) Legal issues
7) Environmental concerns.
8) Estimate of seeding effects

With this brief explanation as background we will now consider the six topics mentioned in the above.

3.3 Program Scope

Definition of the scope of the program needs to include a statement of the goal or goals of the proposed program and definition of the program area. This is an important step. Is a basic operational program desired? Is an operational program with the addition of a number of research type components desired? The answer to the first two questions may be defined by a third question; what is the desired level of proof to establish that the cloud seeding program is working? Are the sponsors of the program willing to employ randomization (a statistical design approach) of the treatment to quantify the effects of seeding? What is considered to be a favorable benefit/cost ratio for the program to proceed? One approach that could be considered is the development of a basic core program that can reasonably be expected to produce some level of increase with optional additions to the program that are prioritized to accomplish the goals of the program. The priority of these additions would be evaluated according to an assessment of the additional cost versus the estimated increase in benefit (i.e., produce more water on the ground; better demonstrate the effectiveness of the seeding, etc.) Other considerations can help refine the generic goals mentioned in the above.

NAWC proposes the following goal for the UBRB: **The stated goal of the program is to increase winter snow pack in the target area to provide additional spring and summer streamflow and recharge underground aquifers at a favorable benefit/cost ratio without the creation of any significant negative environmental impacts.**

NAWC has proposed that the target area include portions of the Upper Boise River Basin above 5,000 feet MSL (refer to Figure 2.4).

3.4 Seeding Agent Selection

The ASCE/EWRI Standard Practice for the Design and Operation of Precipitation Enhancement Programs (ASCE 2004) contains a summary of the different types of cloud seeding agents. That summary is as follows.

> *The materials placed within the targeted clouds are known as seeding agents. While glaciogenic agents intended to increase ice formation are the most common, others having hygroscopic properties are being used with increasing frequency. The full effects of this latter class of seeding agents are only beginning to be explored.*

Precipitation enhancement involves intervening in the microphysical and/or dynamic development of convective cells and stratiform clouds to improve the efficiency of the precipitation processes. The most widely employed method consists of introducing glaciogenic agents, materials which have the capacity to generate additional cloud ice. When added to the natural ice (if any) within the supercooled cloud region, the collective cloud ice population may alter the cloud sufficiently to result in additional rain or snow.

In nature there are many substances which are capable of acting as glaciogenic agents. Not all these substances, however, form ice crystals with the same facility, since their efficiency in this respect is a function of their composition. For example, each substance has a crystallization temperature threshold, which is the temperature at which it begins to cause the formation of ice crystals. In general, it may be said that a substance's ability to act as an ice nucleating agent is higher to the extent that its threshold value approaches the range from 0 to –4^{o}C. The discovery of silver iodide (Agl) as an extremely efficient ice nucleating agent, with a threshold near -5°C, made by Vonnegut (1947), was therefore a major contribution to weather modification activities.

In addition to this widely-used method, there is another which uses a quite different approach (Dennis and Koscielski 1972; Mather et al. 1997). This approach, called hygroscopic seeding, aims to speed the development of large cloud droplets and rain drops through coalescence in the warmer (lower altitude) portions of the cloud. Such accelerated rain development may result in added rain at the ground. Numerical modeling of hygroscopic seeding also indicates that ice processes are enhanced in the seeded clouds.

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).

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.*

Some of the substances used in AgI mixtures are oxidants, and may oxidize (rust) and corrode the metal parts of some IN-generating equipment. Solutions may be obtained pre-mixed, or can be mixed in the field. Care must be taken too that the AgI is thoroughly dissolved, because if it is not, the un-dissolved reagent can block flow in the generator, resulting in generator failures. Once produced, some AgI aerosols may lose some of their glaciogenic capacity with time. Exposure to sunlight, and UV light in particular, may accelerate the deactivation process for some aerosols, while others have shown limited degradation with exposure to sunlight (Super et al. 1975).

As may be imagined from the foregoing, it is of great importance to arrive at a formula for the preparation of silver iodide complexes which provides maximum efficiency, producing the greatest possible number of active IN per unit mass of AgI. Numerous studies have been carried out at Colorado State University using isothermal cloud chambers to analyze the efficiency of different AgI mixtures, and many different formulae have been proposed (e.g. DeMott et al. 1995, Finnegan et al. 1994, Pham Van Dihn 1973, Rilling et al. 1984). Ice nucleus generators may be ground-based, or carried on aircraft, usually at or near the wing tips.

The generation of AgI aerosols can also be accomplished by burning specialized pyrotechnics. In many cases, a mixture containing silver iodate ($AgIO_3$) to diminish the tendency of AgI to break down into its component silver and iodine molecules (Ag and I_2) has been used. Powdered aluminum and magnesium, and some kind of organic agglutinant are also often added to the mixture (Dennis 1980). 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). Speed in nucleation is very desirable in applications such as hail suppression where quick glaciation of modestly-supercooled cloud turrets is required.

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 program; it is sometimes used in conjunction with AgI seeding.

Other Ice Nucleants

Certain proteins derived from a naturally-occurring bacterium, pseudomonas syringae, fall within the description of nucleating proteins, because of their ability to induce the formation of ice crystals in seeding applications. Many other organic substances have this property; among these metaldehyde and 1.5-dihydroxynaphthalene, which have contact freezing temperatures of -3°C and -6°C respectively. Their efficiency in generating ice crystals is very similar to that of dry ice (Kahan et al. 1995).

Hygroscopic Agents

Numerous precipitation enhancement programs have been using AgI complexes as their primary nucleating agent since the 1950s. Nevertheless, the injection of hygroscopic agents which may alter the initial cloud droplet spectra or create raindrop embryos immediately may be an efficient method for treating warm-based continental cumulus clouds, in which the vertical distance from cloud base to the freezing level can be as much as several kilometers. Ludlam (1958) and Appleman (1958) described the concepts involved in hygroscopic seeding with salt particles by dropping large numbers of salt particles into cumulus clouds. Salt seeding was used experimentally in the North Dakota Pilot Program, a combination hail suppression and rainfall enhancement program, in 1972. In this experiment and others conducted in South Dakota, finely ground salt particles were released near the bases of moderate sized cumulus clouds to create raindrop embryos around the salt particles. Experiments carried out in South Africa in the early 1990s underlined the potential importance of seeding with hygroscopic agents. Mather strongly recommends the use of hygroscopic agents to combine hail suppression with precipitation enhancement activities (Mather 1991; Mather and Terblanche, 1994).

Hygroscopic agents deliquesce (that is, become liquid by absorbing moisture from the air) at relative humidities significantly less than 100%. Mather (1991) has made use of flares containing primarily potassium perchlorate , which when burned produces potassium chloride (KCl) particles of about 1 µm diameter. These flares were burned near the base of cumulus clouds in an attempt to alter the cloud droplet spectra. The hygroscopic flares weigh about one kilogram. Although there are many naturally-occurring hygroscopic substances, KCl particles have an advantage of only requiring a relative humidity on the order of 70-80% to deliquesce, and readily act efficiently as CCN.

Program planners should bear in mind that the hygroscopic flare method is relatively new and is not yet used as widely as the AgI complexes, but has shown considerable promise (Cooper et al. 1997, Mather et al. 1996, 1997). A *program in southern France is experimenting with hail suppression based on the new hygroscopic flare technique at the time of writing; other experiments are being conducted in Mexico for rain enhancement (Bruintjes et al. 1999).*

In addition to the possible seeding agents mentioned in the above ASCE reference, there is one other category of possible seeding agents that needs consideration for application in winter cloud seeding programs; this category is liquefied compressed gases. One example of such an agent is liquid propane. The following description is reproduced from Manual #81 prepared by the American Society of Civil Engineers (Kahan, et al, 1995).

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 Program (Super, 1999). A recent randomized research experiment was conducted on the central Wasatch Plateau of Utah testing this agents' possible utility in winter cloud seeding programs (Super and Heimbach, 2005). This paper does indicate seeding increases due to a randomized treatment of storm periods with liquid propane but the area of coverage appeared to be quite small, being on the order of 3-4 km x 3-4 km from a single release point.

NAWC's discussion and recommendations concerning seeding agents to be used on the UBRB are provided in Section 7.

3.5 Targeting and Delivery Methods

The ASCE/EWRI Standard Practice for the Design and Operation of Precipitation Enhancement Programs (ASCE 2004) contains a summary on targeting and delivery methods (seeding mode) associated with cloud seeding programs. The introductory portion of this summary is as follows.

The most critical portion of any cloud seeding program is the proper delivery of cloud seeding material to the appropriate portion of the cloud. Concentrations of the cloud seeding agent must be adequate to modify a sufficient volume of cloud to significantly affect the precipitation process in the desired manner. To date this has been, and continues to be the most critical element in the development and implementation of precipitation enhancement technology.

A number of alternatives exist concerning cloud seeding delivery systems. A basic division exists between these alternatives consisting of ground based or aerial generating systems. Most systems currently in use are designed to dispense silver iodide nuclei, particles of dry ice, or hygroscopic particles. The choice of the delivery system (or systems) should be made on the basis of the program design, which should establish the best system for the specific requirements and the topographic configuration of a given program.

The following section contains specifics on possible seeding modes and targeting issues as related to the UBRB preliminary design.

3.6 Seeding Modes

The specification of the seeding mode(s) and seeding agent(s) for the UBRB preliminary design presents a challenge. In reality there is no one right answer. A number of factors need to be considered to arrive at a reasonable recommendation including effectiveness of the seeding material, cost of the seeding material and delivery mode, reliability of the seeding mode, ability to fly aircraft in the appropriate regions or the ability to locate ground dispensing equipment at preferred locations, ability to disperse the seeding material in the appropriate concentrations somewhat uniformly and continually into the supercooled cloud regions, areas likely to be affected by seeding, and lack of any negative environmental consequences associated with the recommended seeding agents. From this description of factors there is an obvious overlap between seeding modes and the ability to effectively target the seeding material into appropriate cloud regions.

3.6.1 Ground Based Silver Iodide Seeding

Silver Iodide ground based seeding systems are the oldest and most widely used type of seeding mode for winter storms in the western United States. The most common seeding generator burns a solution of acetone in which a certain percentage by weight (usually 2-3%) of silver iodide has been dissolved. Generators can be located at residences upwind of the intended target area and operated by these residents as specified by the program meteorologist. Figure 3.2 provides a photograph of a typical manually-operated unit. Such locations are often in valley or foothill locations. Remotely controlled silver iodide generators are frequently used at higher elevation unmanned locations. Figure 3.3 provides a photograph of a remotely controlled solution-burning

Figure 3.2 Manually Operated, Ground-based Silver Iodide Generator

Figure 3.3 Remotely Controlled, Ground-based Silver Iodide Generator

generator. Ground-based generators normally disperse from 0.4 – 1.6 ounces (10- 40 grams) of silver iodide per generator per hour of operation. Normal consumption rates with these solution-burning generators are on the order of 0.1 – 0.2 gallons (0.4- 0.8 l) of seeding solution per hour of operation. The effectiveness of this type of generator has been established through the conduct of tests at the Colorado State University Cloud Simulation Laboratory. Figure 3.4 provides the results of tests performed on one of NAWC's manually operated generators. **This figure indicates that approximately 8 x 10^{14} ice crystals can be produced from a single gram of silver iodide at a temperature of +14^0 F (-10^{0}C).** This figure also demonstrates that silver iodide becomes increasingly effective with decreasing temperatures. Measurements of naturally occurring ice nuclei (typically soil particles or certain kinds of bacteria) demonstrate this same tendency.

Another method of dispensing silver iodide from ground-based sites is via flares impregnated with seeding material. This approach is used primarily in regions where discrete cloud structures with significant seeding potential can be seeded beneficially via high seeding material dosage rates during their passage over an area. Such seeding sites are commonly remotely operated via computerized control systems. An example is shown in Figure 3.5.

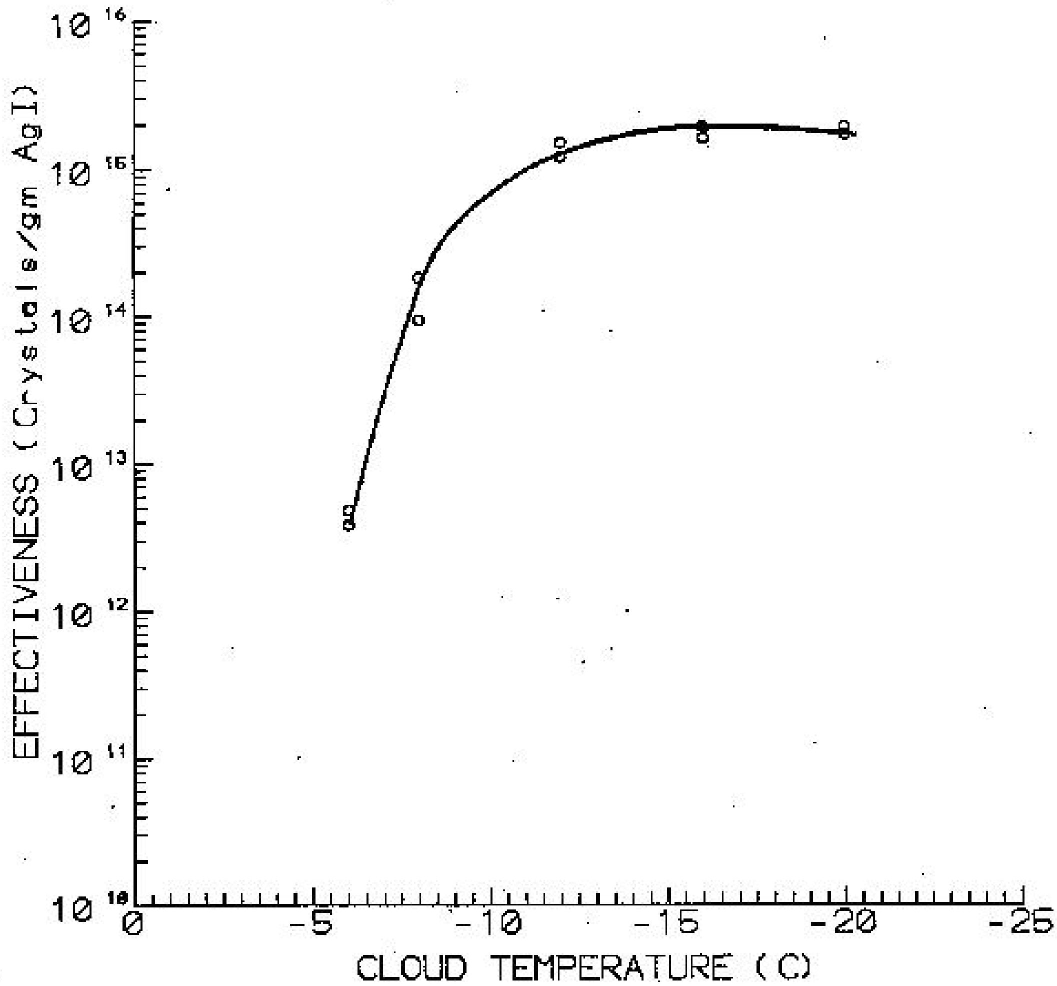

Figure 3.4 Results of Colorado State University Tests of the Effectiveness of a NAWC Manually Operated Ground Based Generator

Figure 3.5 Ground-based Seeding Flare Site

3.6.2 Airborne Silver Iodide Seeding

Seeding with silver iodide using aircraft is the second most common mode of seeding in existing operational winter cloud seeding programs in the United States. In fact, ground generators and aircraft seeding using silver iodide as the seeding agent is a frequently utilized combination-seeding mode. Aircraft seeding to dispense silver iodide is normally accomplished by one of two methods. Flares (similar to highway flares) that have been impregnated with silver iodide can be carried in racks mounted on the trailing edges of the wings. Flares of this type burn in place, i.e., they remain in the wing-mounted racks as they are ignited and burn. Figure 3.6 provides a photograph of a typical installation. Each flare may contain on the order of 1.4 – 7.0 ounces (40 to 200g) of seeding material. The burn duration of these flares is ~ 1 – 5 minutes so the average rate of release is ~ 0.4 – 4.0 ounces (10 – 100 g) of seeding material per minute. Some of these flares have been tested at the Colorado State University Cloud Simulation Laboratory to determine their efficiency. Table 3-1 provides data from a test performed on a flare manufactured by Ice Crystal Engineering (ICE), Inc. of Fargo, North Dakota. This flare exhibited activity up to temperatures as warm as 24.8^0 F (-4^0C). This is a very desirable feature that will be discussed in a later section. The flare formulation also acted very quickly in forming ice crystals, apparently through a condensation/freezing mechanism (in most applications this is also a desirable characteristic).

The other commonly used means of dispensing silver iodide from aircraft is accomplished using acetone/silver iodide generators mounted under each wing tip. These generators hold approximately 8 gallons of a mixture of acetone and silver iodide. This mixture is ignited in the tail cone section of the generator, producing the desired silver iodide particles.

Typical consumption rates of the solution are on the order of 2 gallons per hour per generator, which results in a release rate of approximately 4.2 – 6.3 ounces (120-180 grams) of silver iodide per hour. Figure 3.7 provides a photograph of a typical installation. Work performed by Dr. Finnegan of DRI (Finnegan and Pitter, 1988) indicated that the silver iodide particles produced by these generators also act very quickly if the generator is operated in clouds, due to a transient super-saturation condition resulting from the combustion of acetone producing water in an already saturated environment. Normally airborne generators are operated in-cloud on winter programs. Figure 3.8 provides the results of the tests conducted at the Colorado State University Cloud Simulation Laboratory on a generator manufactured by AeroSystems, Inc. of Longmont, Colorado. These tests indicate that this generator is very effective.

Figure 3.6 Aircraft with Seeding Flare Racks

Table 3-1
CSU Cloud Chamber Test Results for Ice Crystal Engineering Flare

Pyro type	Temp (°C)	LWC (g m^{-3})	Raw Yield (g^{-1} AgI)	Corr. Yield (g^{-1} AgI)	Raw Yield (g^{-1} pyro)	Corr. Yield (g^{-1} pyro)	Yield (per pyro)
ICE	-3.8	1.5	$3.72x10^{11}$	$3.87x10^{11}$	$4.01x10^{10}$	$4.18x10^{10}$	$6.27x10^{12}$
	-4.0	1.5	$9.42x10^{11}$	$9.63x10^{11}$	$1.02x10^{11}$	$1.04x10^{11}$	$1.56x10^{13}$
	-4.2	1.5	$1.66x10^{12}$	$1.70x10^{12}$	$1.80x10^{11}$	$1.84x10^{11}$	$2.76x10^{13}$
	-4.3	1.5	$2.15x10^{12}$	$2.21x10^{12}$	$2.32x10^{11}$	$2.39x10^{11}$	$3.53x10^{13}$
	-6.1	1.5	$6.01x10^{13}$	$6.13x10^{13}$	$6.49x10^{12}$	$6.62x10^{12}$	$9.93x10^{14}$
	-6.3	1.5	$5.44x10^{13}$	$5.56x10^{13}$	$5.87x10^{12}$	$6.00x10^{12}$	$9.00x10^{14}$
	-6.4	1.5	$6.22x10^{13}$	$6.34x10^{13}$	$6.72x10^{12}$	$6.85x10^{12}$	$1.03x10^{15}$
	-10.5	1.5	$2.81x10^{14}$	$2.85x10^{14}$	$3.03x10^{13}$	$3.07x10^{13}$	$4.61x10^{15}$
	-10.5	1.5	$2.34x10^{14}$	$2.37x10^{14}$	$2.87x10^{13}$	$2.91x10^{13}$	$4.37x10^{15}$
	-4.2	0.5	$1.41x10^{12}$	$1.45x10^{12}$	$1.53x10^{11}$	$1.57x10^{11}$	$2.36x10^{13}$
	-6.0	0.5	$7.42x10^{13}$	$7.73x10^{13}$	$8.01x10^{12}$	$8.34x10^{12}$	$1.25x10^{15}$
	-10.5	0.5	$2.38x10^{14}$	$2.41x10^{14}$	$2.91x10^{13}$	$2.96x10^{13}$	$4.44x10^{15}$

Figure 3.7 Aircraft with Silver Iodide/Acetone Generators

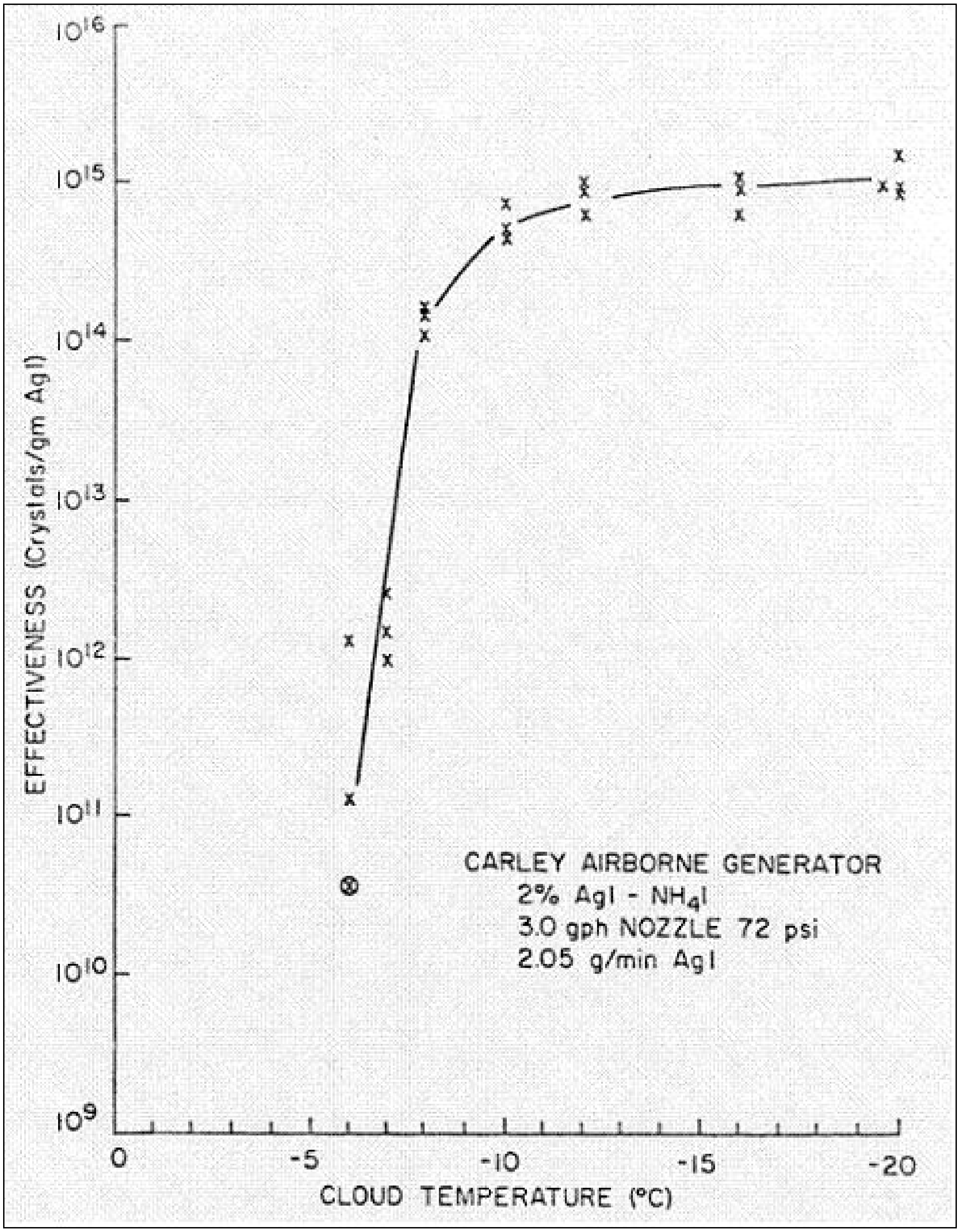

Figure 3.8   CSU Cloud Chamber Tests of AeroSystems Generator

A third means of dispensing silver iodide from aircraft consists of racks mounted on the bottoms of aircraft fuselages (see Figure 3.9). These racks are then loaded with flares that can be fired vertically downward. The payloads of seeding material in these "ejectable" flares fall away from the aircraft, traveling about 2000 to 6000 feet vertically before being completely consumed through combustion. This seeding mode is frequently used in seeding isolated towering cumulus clouds via "on top" cloud penetration seeding on summer programs, but is seldom used in winter programs due to the expense involved in seeding large areas in a nearly continuous fashion.

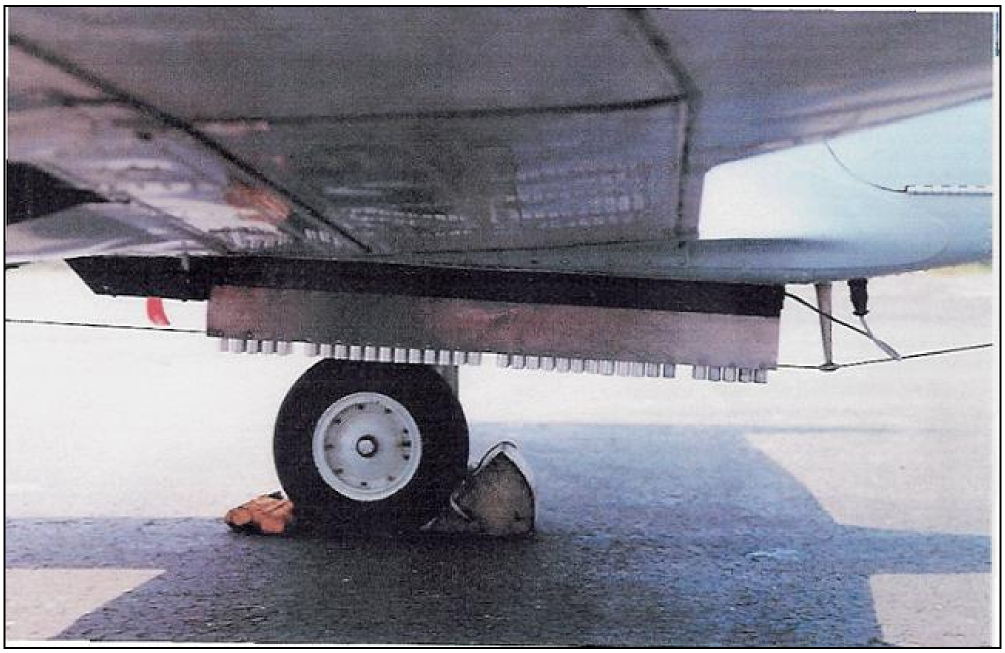

Figure 3.9 Aircraft Belly Mount, Droppable Silver Iodide Seeding Flare Rack

3.6.3 <u>Airborne Seeding with Dry Ice</u>

A less commonly used mode of seeding winter storms is airborne seeding using dry ice (this particular seeding mode is more commonly used to disperse cold fogs at airports to allow aircraft to land and takeoff by improving runway visibilities). Oftentimes dry ice pellets with diameters of 0.2 – 0.4and lengths of 0.4 - 1" in length are carried onboard aircraft in hopper/dispensing systems and are dispensed through the floor of baggage compartments or extra passenger seat locations on modified cloud seeding aircraft. These pellets will fall about 3300-6600 feet before they completely sublimate. Typical release rates are from one pound to a few pounds of dry ice per mile of flight path. Dry ice is an effective ice nucleant, producing 2 X 10^{11} to 8 X 10^{11} ice crystals per gram of dry ice dispensed. Its effectiveness is relatively independent of temperature in the range of 30^0 – 12^0 F (-1^0C to -11^0C) (Holyroyd, et al, 1978). Figure 3.10 provides a photograph of a dry ice dispenser mounted in a seeding aircraft.

3.6.4 <u>Ground Based Propane Seeding</u>

Some investigators have suggested that the use of liquid propane as a seeding agent should be considered since it theoretically could produce ice crystals near the freezing level, while silver iodide does not begin to become effective until temperatures of 23 to 25^0 F (-4 or -5^0C) are reached. Some research (e.g., Super, 1999) has indicated that there are periods near the crests of mountains in the west that experience significant periods of supercooled liquid water at temperatures in the 32^0 to 23^0 F (0 to -4^0C) range in which liquid propane seeding may be effective while silver iodide would not be. There has only been one research-oriented program that used liquid propane as the seeding agent that was designed to produce an effect over a sizable target area (Reynolds, 1994). The program was terminated after three winter seasons of seeding with no indication of any positive seeding effects. Recent research conducted in Utah (Super and Heimbach, 2005) did demonstrate positive seeding effects using this technique, but apparently only over a very small area. It is NAWC's position that positive results are needed from a research program conducted over a sizable area before this technique is considered for use on operational winter cloud seeding programs. A statement in ASCE Manual 81 supports this position. This statement is "Future experimentation needs to be conducted to demonstrate that this technique can increase precipitation over a fixed target area for a significant period of time (e.g., a winter season)." NAWC, for the reasons stated herein, does not recommend the use of liquid propane as a seeding agent on the UBRB.

Figure 3.10 Dry Ice Dispenser Mounted in a Seeding Aircraft

3.6.5 General Discussion on the Considerations that Govern the Specification of a Seeding Mode(s)

The goal of a wintertime orographic cloud seeding program is to convert supercooled liquid water droplets (SLW) upwind of and over the mountain barrier(s) into ice crystals in a timely fashion, such that they have time to grow into snowflakes and fall within the intended target area. From the discussions contained in Section 3.1 we believe that the primary area of opportunity is over the upwind slopes of the mountain barrier extending to heights of perhaps 1600 – 3300 feet above the crest of the mountain barrier. Figure 3.11 is a stylized schematic depiction of this zone of opportunity. It appears that this zone of SLW is frequently present in winter storms, although it does appear that SLW concentration and extent fluctuate with storm conditions. For example, if there are deep clouds upwind and over the barrier there may be enough natural nucleation occurring in the colder portions of these clouds such that the natural precipitation processes are efficient in removing any lower level SLW. Under these conditions precipitation rates may be substantial but there is little, if any, opportunity for seeding to increase snowfall rates. It appears that shallower cloud systems and those that contain embedded convection[1] are more likely to have significant periods with the lower level SLW profile as depicted in Figure 3.11.

There are a number of considerations that impact the ability to fill this zone of opportunity in a timely fashion with seeding materials in sufficiently high concentrations to produce a positive effect of seeding in the target area. Several of these considerations are time related. For example, how long does it take to transport silver iodide nuclei from ground generators into this zone of SLW at cold enough temperatures for the silver iodide to nucleate cloud droplets forming ice crystals? Then how long does it take for these ice crystals to grow into snowflakes that are large enough to fall to the ground? This transport, nucleation, growth, and fallout scenario is directly impacted by the wind speeds that are encountered at different stages in this scenario. Stronger wind speeds will mean that the effects of cloud seeding (if any) will occur at increased distances from the release point. The seeding agent used is also related to these timing issues. If one possible ground based seeding agent threshold is 23^0 F (-5^0C) and another is 28.4^0 F (-2^0C), it will take longer for the agent active at 23^0 F (-5^0C) to reach its nucleation level than the one that begins to nucleate at 28.4^0 F (-2^0C). Cloud chamber tests also indicate that some seeding agents act very quickly through a condensation/freezing mechanism, while others act more slowly though a contact freezing mechanism. These differences can impact where the effects of seeding occur from a given ground release point.

[1] Embedded convection – convective cells, embedded in a stratiform cloud deck, that promote upward vertical motion.

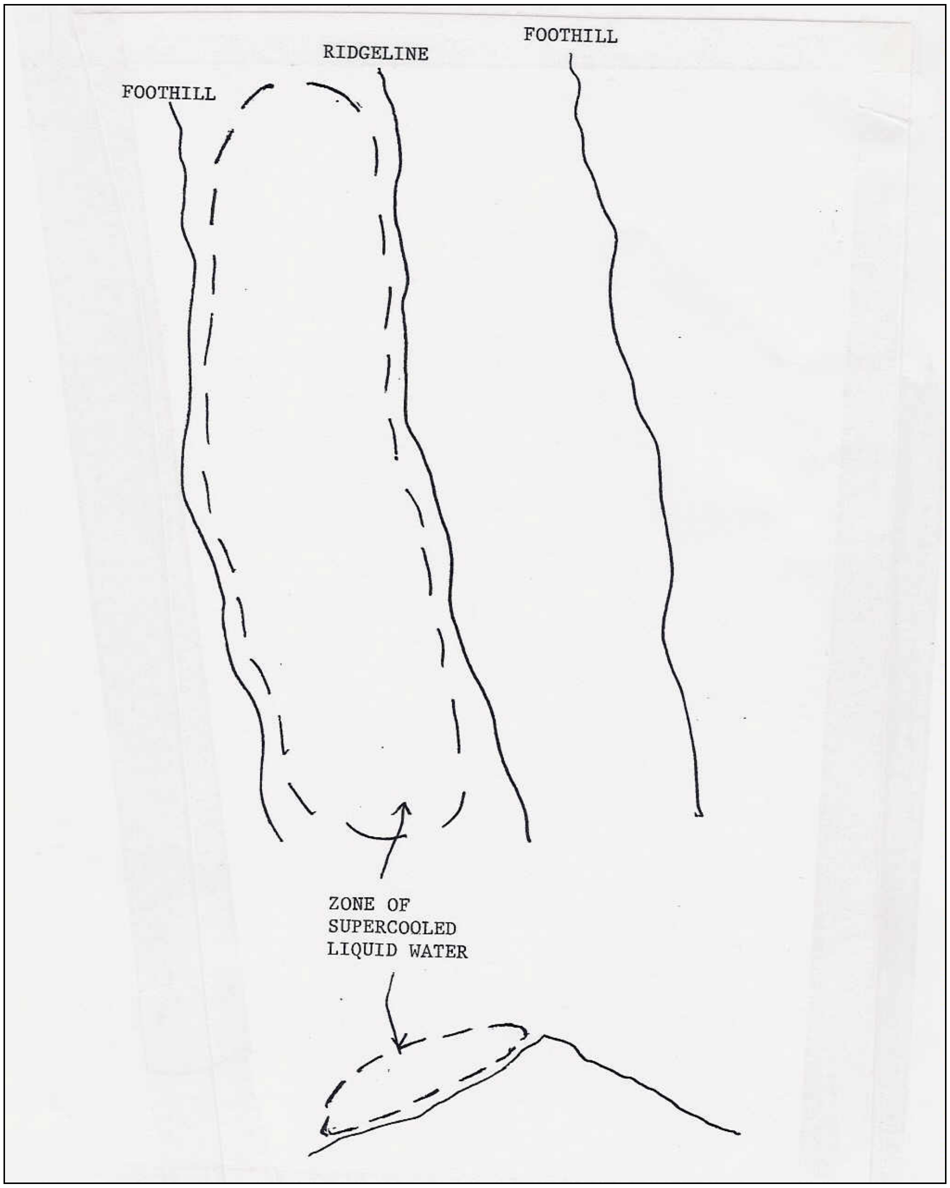

Figure 3.11 Stylized Depiction of SLW Zone on Upwind Side of a Barrier

One of the other considerations is how to fill a majority of this SLW zone in a satisfactory way. In other words, how well do the seeding plumes merge or overlap horizontally to fill this volume? Consideration of this question in combination with the expected lower level wind flows that will be encountered upwind and over the target area will lead to the development of the proposed spacing and location of ground generators. A network of generators will typically be needed to be able to effectively seed under a variety of different wind directions. Not all such generators will be used to seed at the same time, but differing combinations of generators will be used to correctly target the seeding material with changing wind directions. In a similar manner, aircraft seeding tracks need to allow flexibility to account for these changing conditions.

3.6.6 Advantages and Disadvantages of Ground Based Generators

There are advantages and disadvantages associated with manually operated and remotely controlled ground based seeding devices (typically ground based silver iodide generators). Some research (e.g., Super, 1999**)** has suggested that there may be low-level atmospheric temperature inversions[2] during winter storm periods that may trap the silver iodide particles released from valley or foothill based ground generators. NAWC has found that such inversions certainly do occur, but the strength, height and frequency of such inversions vary considerably from one area to another. An earlier NAWC feasibility/design study (North American Weather Consultants, 2002) conducted for the Uintah Basin in northeastern Utah documented that low-level atmospheric inversions were a fairly frequent phenomenon in that region during the wintertime.

There were two types of inversions identified: 1) ones that were based near the surface, and 2) ones that were elevated. The height of the tops of the surface based inversions averaged 1340 feet above ground level, or at an elevation of 6290 feet MSL. The tops of the elevated inversions were also relatively low, being on the order of 2600 feet above ground level or at an elevation of ~7570 feet MSL. In order to address the concerns about the possible trapping of silver iodide released from valley locations, NAWC recommended that seeding sites for that program be located above the average top height of the elevated inversions (i.e., at or above ~ 7,600 feet in elevation). This would potentially avoid trapping of the silver iodide seeding material in at least half of the occurrences with elevated inversions, and a large majority of those cases with surface based inversions. The clients accepted this data analysis-based approach, and suitable sites were found which could utilize manually operated units (similar to Figure 3.2). These manually operated units are far less expensive to fabricate, install and maintain than remotely controlled units. In central Utah, a case study that utilized tracer data to document the likely plume transport of seeding material found that seeding material released beneath a low-level inversion from a valley site between two mountain ranges was transported over the second barrier (Heimbach, et al, 1997). The explanation given by the authors was that apparently a gravity wave[2] was responsible for the transport of the seeding material through the inversion.

Research work conducted in Utah, summarized by Super (1999), suggested that transport from valley generators was limited and that concentrations of silver iodide were too low when transport did occur. There are least two problems associated with these conclusions: 1) some flights conducted to determine if valley released seeding materials were being transported over the crest were conducted under Visual Flight Rule (VFR) conditions in order to allow the aircraft to fly at low altitudes over the barrier, and 2) concentrations of seeding material were primarily inferred from counts recorded on a device known as an NCAR counter. In regards to the first point, it is NAWC's position that atmospheric conditions are different during active storm periods than they are in pre-frontal VFR conditions. The presence of lower level inversions (indicated to occur ~37%

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[2] Oscillations over or downwind of mountain barriers resulting in a repeating pattern of upward and downward motions typically organized in waves.

of the time based upon valley rawinsonde observations) may not be a problem anyway if there is no supercooled liquid water associated with such occurrences. It is unknown whether supercooled water existed in these cases, since no stratifications of the data were presented using these criteria. Interestingly, this paper does indicate successful transport of valley-released silver iodide to the crest line in 90% of seven different relatively wet cases with supercooled liquid water present. The explanation given was that at most times when supercooled liquid water was present in amounts of 0.002 inches or more (i.e. the better cases), weak embedded convection was also present, which likely assisted vertical transport of the valley released silver iodide. Regarding the second point, it is our opinion that counts of ice nuclei observed on an NCAR counter at -4^0 F (-20^0 C) can be very unreliable. This position is supported by the fact that the actual counts observed by the NCAR counters are often multiplied by 10 to account for possible accumulation of ice crystals on the sidewalls of the device. Further, the crystal growth times in NCAR counters are only on the order of approximately three minutes. We know from cloud chamber tests conducted at Colorado State University that activation of silver iodide particles may take as long as 15-20 minutes. This is another likely source of undercounting of the silver iodide nuclei that may be present.

Finally, there have been evaluations of the operational programs being conducted in Utah using lower elevation silver iodide generators that indicate that this (ground generator) type of cloud seeding is effective (Griffith, et al, 2009). There are no doubt winter periods in Utah and in other western mountain ranges when seeding from low level generators will be ineffective. Whether the addition of higher-elevation remotely controlled generators to seed more effectively under these conditions is warranted must be examined in light of the additional costs and logistical complications involved versus the estimated increment in additional precipitation that may be produced by using such systems.

Going back to the timing discussions found in section 3.6, a case can be made that it is better to locate the generators upwind of the mountain barriers (usually at lower elevations) since this may allow seeding material reaching effective levels well upwind of the crest. In this scenario, longer growth times are available for the ice crystals to reach snowflake sizes and to fall on the barrier. Placing remotely-controlled generators near the crest lines of these barriers (as has been done on research programs such as the Bridger Range and Utah NOAA programs) may result in only very small snow flakes being formed on the upwind side of the barrier (due to the short times for growth), which may not contribute significantly to the overall water balance on the upwind side of the barriers. Any positive effects are more likely to occur on the downwind side of the barriers. Generation of significant effects in downwind areas, however, will be hampered by descending air motions on the lee side of the barriers, which may result in poor growth of the snowflakes due to lack of significant SLW and warming temperatures, factors which may actually result in sublimation (a phase change going directly from solid to vapor) of some of the snowflakes. In this scenario, the water content contained in the artificially generated snowflakes may never reach the ground. In fact, the Bridger Range experiment (Super, 1986) was designed for seeding over a first barrier to produce effects over a secondary downwind barrier located approximately 8 miles downwind. This experiment was successful in accomplishing this goal, but these results are only transferable to locations that have dual barriers or perhaps multiple barriers located at similar distances downwind from the first barrier. In these situations, downslope descending flow may not develop (or not develop very strongly) since the second barrier provides orographic uplift to the air mass.

To generalize, seeding the relatively narrow mountain barriers typical of the Intermountain West with remotely controlled generators located well up the windward side of these barriers will probably only produce appreciable positive effects near the crest and on the immediate downwind slopes of these barriers. In other words, little or no seeding effect would be expected on the upwind slopes of these barriers. Unfortunately, higher amounts of precipitation normally occur on the upwind slopes of such barriers, so a major opportunity to provide significant amounts of additional water may be limited. To illustrate, a 10% increase on a 25" base is 2.50", whereas a 10% increase on a 15" base amount would be 1.5". In addition, if seeding can be accomplished from generators located further upwind of the barriers, some of these effects would be expected to affect the downwind slopes of the mountain barrier as well. Finally, recall that the majority of the SLW and thus seeding potential is expected to occur on the upwind side of the barriers (refer to Figure 3.1). Remotely controlled generators located near the crest would be missing a large majority of the SLW, which would be located further upwind of those generators. Mountain barriers which are fairly broad offer a better potential than do narrow ranges for the location of remotely controlled generators at mid- to upper-elevations, which still have the potential of impacting more of the SLW zone and also have the advantage of being far enough from the barrier crest to allow snowflakes to grow in favorable growth regions and fall on a portion of the upwind side of the barrier. An excellent example of such a situation is the Sierra Nevada in California where a number of long term programs have effectively employed remotely controlled ground generators. Interestingly, some of these programs also employ lower elevation, manually operated units.

Releases of seeding material further upwind also allow more time for the seeding plumes to spread horizontally, perhaps even overlap, thus potentially affecting larger areas. This important effect is demonstrated in a schematic fashion in Figure 3.12.

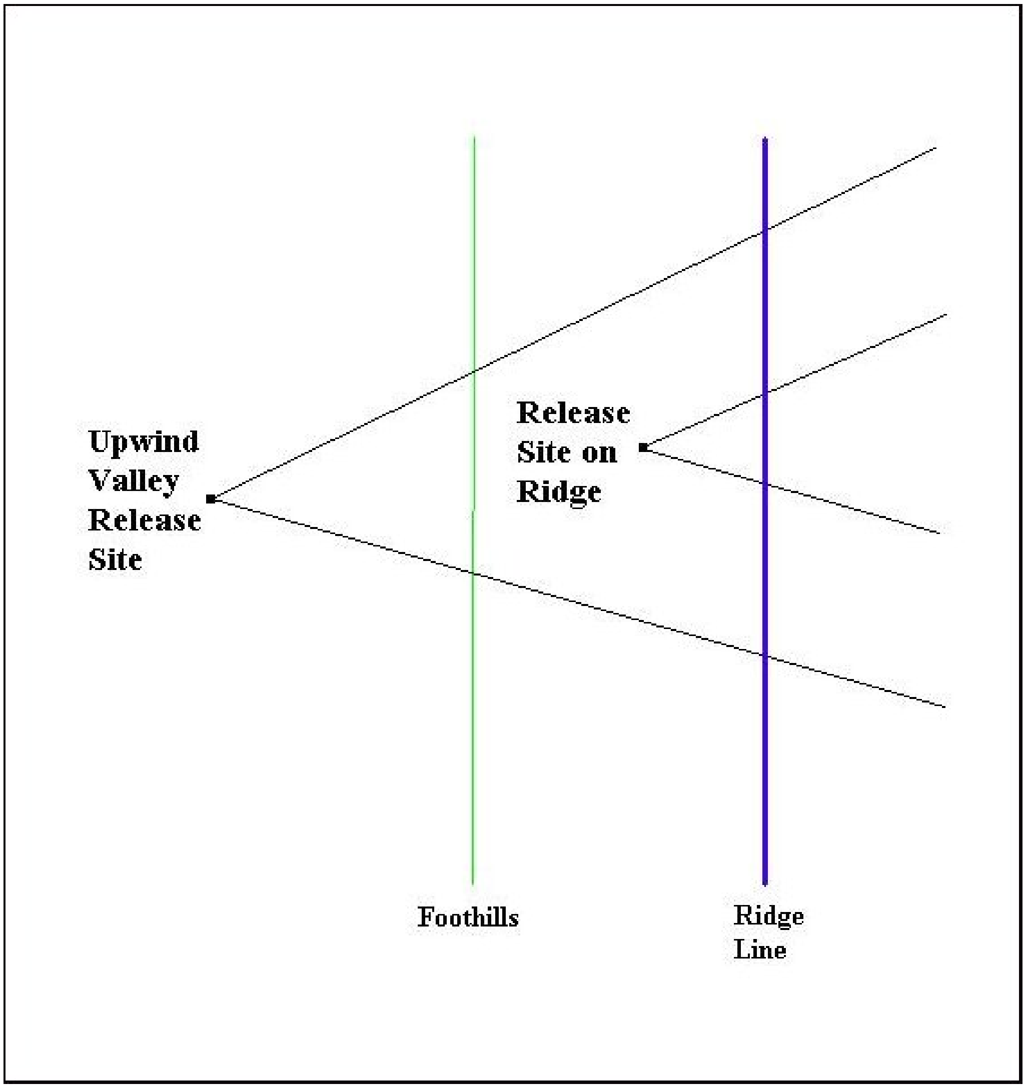

Figure 3.12 Illustration of Seeding Plume Spread (black lines) from an Upwind Valley Site and a Site near the Ridge Line

Other advantages of ground generator systems (compared to aerial seeding) include lower cost of operation and the ability to operate continuously for extended periods. Ground generators also can be operated to affect mountainous target areas during winter storms under shallow orographic cloud conditions that are impractical or unsafe to seed using aircraft. These conditions can occur for extended durations in winter storms and frequently offer favorable seeding situations.

Disadvantages of ground-based seeding include greater targeting uncertainty; since assumptions have to be made regarding the combined horizontal and vertical transport of seeding material as well as in nuclei activation, ice crystal growth, and fallout time. The high cloud seeding rates possible with aircraft at effective cloud seeding heights (i.e., colder than about 24.8^0 F (-4^0C)) are probably not possible using a ground generator system. Another possible disadvantage is that use permits from federal agencies (e.g., U.S. Forest Service) are frequently required in order to site remotely controlled generators on federal lands. Requests for use permits on federal lands may trigger the need to perform an environmental assessment for the program. Also, maintenance of remotely controlled generators in isolated locations often requires costly, regularly scheduled maintenance trips involving over-snow vehicles or helicopters.

Most of the above comments dealing with remotely controlled silver iodide generators would also apply to seeding using releases of liquefied propane, especially since these systems must be in-cloud at temperatures $<0^0$C to have any effect. This operating characteristic forces installations at higher elevations, which results in concerns regarding the nucleation and growth time issues discussed elsewhere in this section. The main advantage of seeding with propane is that it will create ice crystals at warmer temperatures than silver iodide (threshold temperatures of perhaps 30.2^0 F (-1^0 C) instead of 24.8^0 F (-4^0 C). As Super (1999) points out, supercooled liquid water may occur rather frequently in the temperature range of 30.2 – 24.8^0 F (-1 to -4^0 C) during portions of winter storms in the Intermountain West where silver iodide seeding would be ineffective. It should be noted again, however, that the growth rates of ice crystals are relatively slow in this temperature range compared to growth rates at 17.6^0 F (-8^0 C).

Propane dispensers must be located at locations where the temperatures are below $+32^0$ F (0^0 C) and releases must be made in cloud. These conditions dictate that the dispensers be located well up the windward side of the mountain range, thereby invoking some disadvantages in the case of a narrow mountain range as mentioned earlier. Seeding effects are only produced in a small cone (perhaps 12" in diameter and 36" in length) of supercooled air that results from the venting of the liquid propane. Seeding effects are instantaneous through homogeneous freezing of the supercooled water droplets. There are, however, no downwind effects. By comparison, silver iodide particles can be released in upwind valleys at temperatures above freezing and then proceed to nucleate supercooled liquid droplets several miles downwind. This feature offers the opportunity to potentially treat much larger areas from a single silver iodide generator than from a single propane dispenser.

3.6.7 Advantages and Disadvantages of Airborne Seeding

Seeding winter clouds with silver iodide from aircraft offers some attractive features. Theoretically, an aircraft may be flown at flight levels at which silver iodide will activate immediately (~ 23^0 F or -5^0C and colder) without the requirement for the silver iodide to rise from a ground source to these levels. Aircraft may also be flown at locations selected to effectively target the intended target area(s). Aerial systems also offer advantages in terms of the ability to deliver higher seeding rates into given volumes of cloud, and the ability to seed stable atmospheric situations that may not be effectively treated using ground-based systems.

Disadvantages of aerial seeding include higher costs (much greater than ground generator operations). It also is difficult to maintain an effective amount of cloud seeding material feeding into clouds affecting a target area over long periods of time and of perhaps substantial size (i.e., multiple aircraft may be required). In addition, there are potential hazards of flying in icing conditions or extreme turbulence, and there are possible flight restrictions near major airports and within Military Operations Areas (MOAs). The Federal Aviation Administration also restricts minimum altitudes that may be flown in a specific area under Instrument Flight Rule (IFR) conditions (e.g., cloud obscured conditions). The general restriction is that the aircraft may not fly less than 2,000 feet (610 m) above the highest terrain located 5 nautical miles either side of the proposed flight path. This last item has proven to present a problem in an attempt to use aircraft to seed in some winter orographic programs, e.g., a program conducted by Idaho Power on the Payette River Drainage in Idaho (Riley and Chavez, 2004).

There are two concerns which are interrelated: 1) can an aircraft be flown at low enough altitudes to effectively target the low-level SLW which seldom extends above the crest of the mountain barrier, and 2) can it be done safely? The answer to the questions will depend upon the topography upwind of the intended target area and the height of the freezing level during storm periods. For example, if there is a second mountain barrier upwind of the target barrier and it is 10 miles between the mountain ranges with a narrow valley between, then the aircraft could fly no lower than 2,000 feet above the crest height of the barriers, which would mean it would be flying above the top of the seedable SLW layer. This would make the seeding ineffective. If the spacing between barriers is greater, with an intervening valley, then the aircraft may be able to fly along the axis of the valley at low enough altitudes to effectively target the SLW layer over the downwind barrier. The ability to conduct effective targeting in this scenario is confounded by the tendency of the air parcels flowing over mountain barriers to rise over the mountain barrier in stable to neutral stability situations. This could mean that the seeding material could still rise above some or all of the SLW, again resulting in ineffective targeting. This scenario is depicted schematically in Figure 3.13.

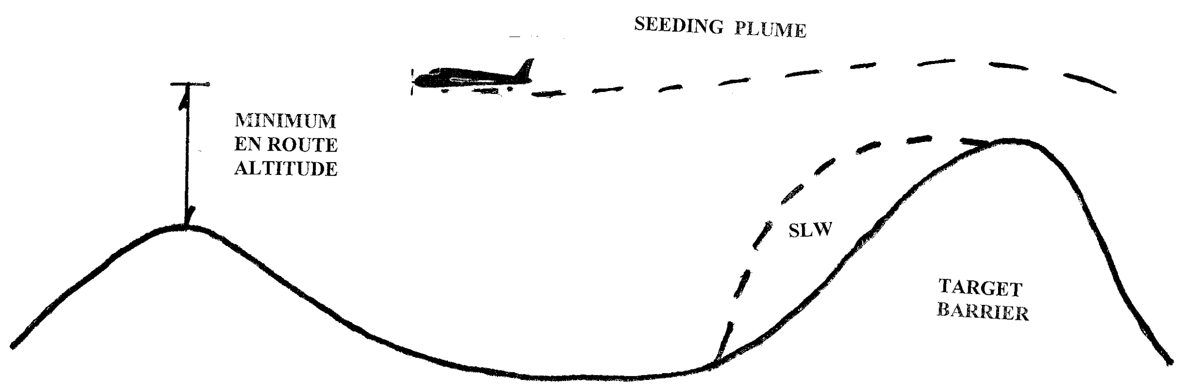

Figure 3.13 Schematic of Aircraft Seeding Upwind of a Mountain Barrier

A further complication arises if the freezing level is within about 2000' above the valley floor. In these conditions, if the aircraft encounters icing (which is likely), it cannot descend to temperatures warmer than freezing to melt off the ice while airborne. High performance aircraft, which can be a costly approach, may be necessary to overcome this potential problem out of concern for the safety of the aircraft crew. Even so, it may be difficult to maneuver the aircraft within the valley in order to make 180 ^{o} turns in order to remain upwind of the target area. The aircraft will typically be flying under IFR flight rules (in cloud) so the pilot cannot necessarily see the underlying terrain to make these maneuvers. These situations may force the aircraft to fly at higher altitudes (to maintain terrain clearance) that may result in seeding plumes being generated above the SLW zone, as illustrated in Figure 3.13.

Aircraft seeding in winter storms is quite common in the Sierra Nevada of California. Primary factors in this area is that the upwind San Joaquin Valley (west of the Sierra) is quite wide and that the height of the freezing level in winter storms in this area is typically significantly above the valley floor. As a consequence, seeding aircraft can fly at about the 23^{0} F (-5^{0} C level), an effective flight level for silver iodide seeding due to the activation threshold of silver iodide being ~ 24.8^{0} F (-4^{0}C), and readily descend to altitudes warmer than freezing to shed any ice build up without the requirement to land. Lower performance aircraft can be safely operated in this environment. The seeding is also likely to be effective since the aircraft may be flown at low enough altitudes that the seeding material will encounter the SLW pool well upwind of the barrier in time for the growth and fallout of augmented precipitation on the upwind side of the barrier. Physical studies of the silver plus tracer content of snow samples taken from one of the long-term target areas in the Sierra Nevada confirm that silver released from aircraft is found in a significant portion of these snow samples (McGurty, 1999).

3.6.8 Summary

All of the information contained in Sections 3.1 through 3.6 is utilized in combination with specific considerations (e.g., topography, climatology) associated with the proposed target areas, to identify the recommended seeding agents and seeding modes in Section 7.

4.0 REVIEW AND ANALYSIS OF THE CLIMATOLOGY OF THE TARGET AREA (TASK 1)

The meteorological parameters of greatest interest in this feasibility study are: precipitation, surface and upper-level wind directions and velocities, temperatures at the surface and aloft, and the structure of the lower to mid-levels of the atmosphere. Information on these parameters during winter storm periods that impact the proposed target area is of primary interest. Two factors drive these considerations: 1) the likely presence of "seedable" conditions, and 2) the potential ability to target these seedable regions. Considerations involving the first factor (seedability) may be focused on the temperatures and winds within the storms. To be seedable, a portion of the cloud system needs to be colder than freezing. Also, the height of certain temperature levels such as the 23^0 F (-5^0 C) are important for one of the primary seeding materials (silver iodide), since this is the warmest temperature at which silver iodide begins to be active as an ice or freezing nuclei. Another consideration may be the speed and direction of the lower level winds. If winds are blowing up and over the mountain barrier and the cloud top temperatures are not too cold, then supercooled liquid water droplets will likely be present in the storm clouds. It is the presence of these supercooled water droplets that determine whether there is any seeding potential within the clouds. A photograph illustrating the extreme build up of ice that was formed from supercooled water droplets impacting structures on the top of Mt. Washington in New Hampshire is provided in Figure 4.1. Targeting considerations are related to the likely transport and diffusion of seeding materials, which becomes a function of seeding mode (ground based, aerial), the lower level wind speed and direction, and lower level atmospheric stability. These targeting issues were discussed in sections 3.5 and 3.6.

Information on these parameters of interest is provided in the following sections. This feasibility study was defined as a wintertime activity. We have therefore provided information for the October through April time frame.

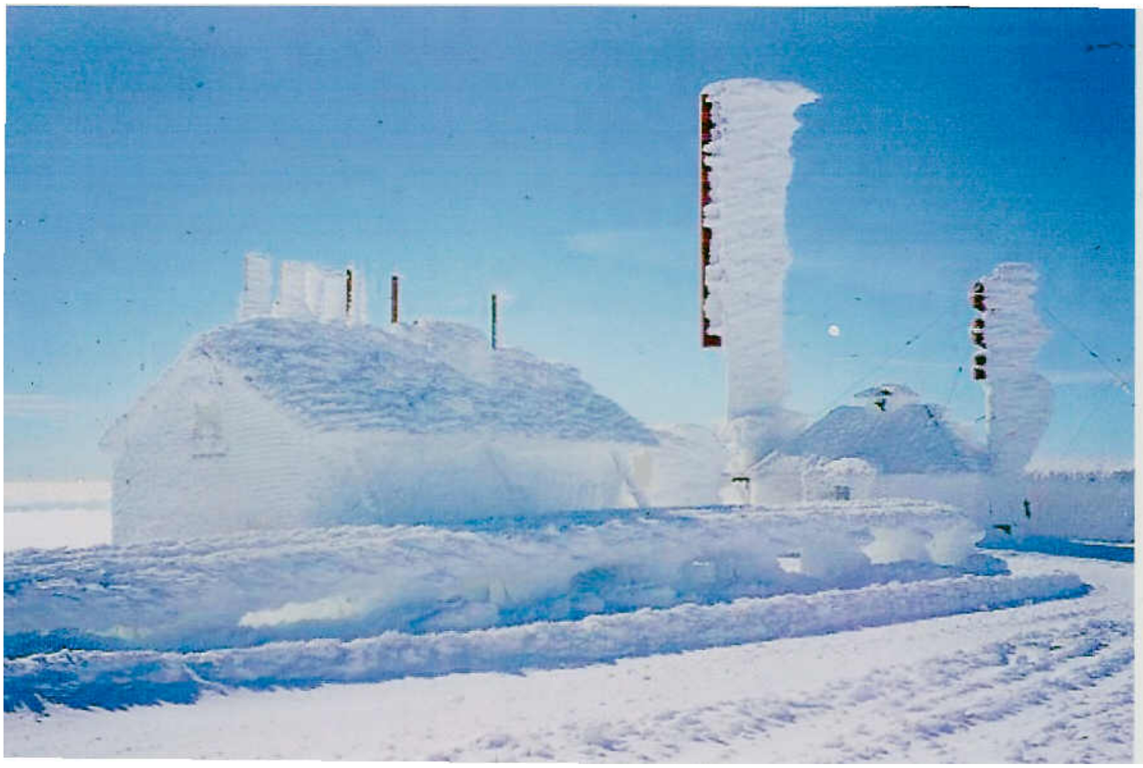

Figure 4.1 Riming on Mt. Washington, NH

4.1 Precipitation and Snow Water Content

Data on the natural precipitation of the program target area provides useful information concerned with the different types of storms that impact this area. Such data also provide a baseline for estimation of the magnitude of precipitation increases that may be possible through cloud seeding. For example, if a potential target site receives an average 30 inches of precipitation during the winter months and if our analyses indicate that a 12% increase in precipitation is possible from cloud seeding, then the estimated increase in an average winter season at this site would be 4.5 inches of additional precipitation. This estimate may then be used to provide estimates of resultant increases in steamflow. Observations of precipitation in the higher elevation target area have primarily been made by the Natural Resources Conservation Service (formerly the Soil Conservation Service). These observations are of two basic types: 1) measurements of snow water content and 2) measurements of rainfall and melted snowfall.

Manual observations of the water content of snowfall throughout the mountainous areas of the west began in 1906 through the pioneering work on manual snow water measurement techniques by Dr. Church in the Reno, Nevada area (Church, 1918). These measurements were mandated by Congress to “measure snowpack in the mountains of the West and forecast the water supply.” Sampling locations were established throughout the mountain ranges of the west. Typically a high elevation snow course was visited approximately once per month during the winter months and ten vertical measurements of the snowpack were taken each month with a hollow tube that converted the weight of the snow into a water content measurement in inches. The ten observations were then averaged to give an estimate of the snow water content in inches for the snow course. Some of these snow course sites were also equipped with stand pipe storage gages. These storage gages were charged with an anti-freeze solution, which melted the snow as it fell into the gage. A pressure transducer provided the resultant precipitation amount in inches of water. The crews making the snowcourse measurements would also record the standpipe storage gage precipitation amounts at those sites equipped with such devices. The Soil Conservation Service implemented a major improvement to this measurement technique in the early to mid-1980's. This new technique was called SNOTEL (for SNOwpack TELemetry). SNOTEL utilizes a unique data transmission system that relies upon meteor burst technology. VHF radio signals are reflected at a steep angle off the ever-present band of ionized meteorites existing from about 50 to 75 miles above the earth. With the advent of the SNOTEL system, data are available with approximately hourly resolution. The data typically consist of snow water content, precipitation and temperature. A snow pillow, which is a cylindrical metal device approximately 8 feet in diameter and 4 inches in thickness, measures snow water content. Precipitation is measured with the same standpipe storage gages described previously.

Figure 4.2 provides a photo of an NRCS SNOTEL site taken in the fall, to allow the reader a better understanding of the two types of observation systems. The vertical tube is the standpipe storage gage, which is approximately 12" in diameter. The gages are approximately 20' in height so that their sampling orifices remain above the snowpack surface. In the fall, the storage gage is charged with antifreeze, which melts the snow that falls to the bottom of the gage. A pressure transducer records the weight of the solution. The weight of the antifreeze is subtracted from the total weight, giving the weight of the water, which is then converted into inches.

There are at least two types of problems associated with high elevation observations of the water equivalent of snowfall. There are potential problems associated with each type of observation. The two areas of concern are clogging at the top of the standpipe storage gage, and blow-by of snowflakes past the top of the standpipe gage. Either situation would result in an underestimate of the actual precipitation that fell during such periods. Heavy, wet snow may accumulate around the top of the standpipe storage gage, either reducing or stopping snow from falling into the standpipe and resulting in an underestimate of precipitation. Snow that falls with moderate to strong winds may blow past the top of the gage, which can also result in an underestimate of precipitation. NRCS sites are normally located in small clearings in forested areas to help reduce the impacts of wind problems. Sites that are near or above timberline are more likely to be impacted by wind since sheltered sites may be difficult to find in these higher elevation areas.

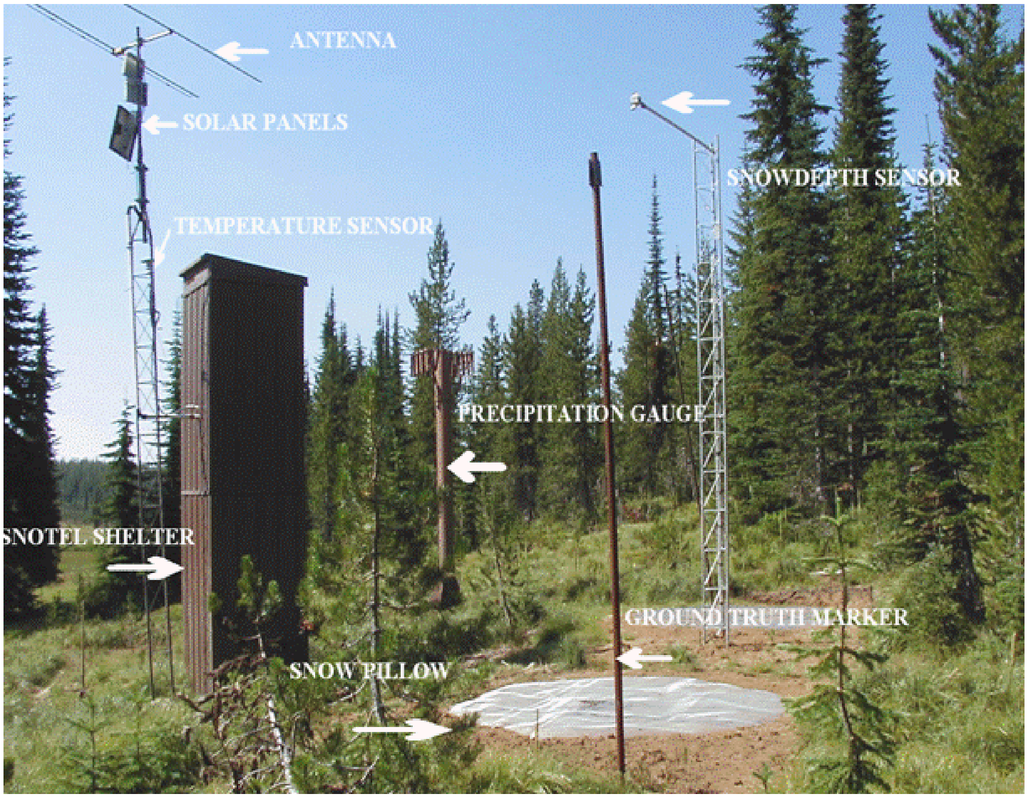

Figure 4.2 Example of an NRCS SNOTEL site

The snow pillow pictured in the foreground in Figure 4.2 is filled with antifreeze. This system weighs the snowpack, providing time-resolved records of the snowpack water content. Snow pillows can also have difficulty in providing accurate measurements of snow water content, because of wind either adding or removing snow from the measurement site when snow conditions are favorable for drifting. Consequently, either measurement should be considered an estimate of the actual amount of precipitation that falls.

There are several NRCS precipitation and snow observation sites that have long-term records in the proposed target area. Figure 4.3 is a map of these site locations. Table 4-1 provides the 1971-2000 average monthly amounts of precipitation, and Table 4-2 the average monthly snow water equivalent data, at these SNOTEL sites. Table 4-3 compares precipitation during the October - April season with the average annual totals at these sites. Average monthly precipitation and winter season snow water accumulation for the Atlanta Summit site are shown in Figures 4.4 and 4.5.

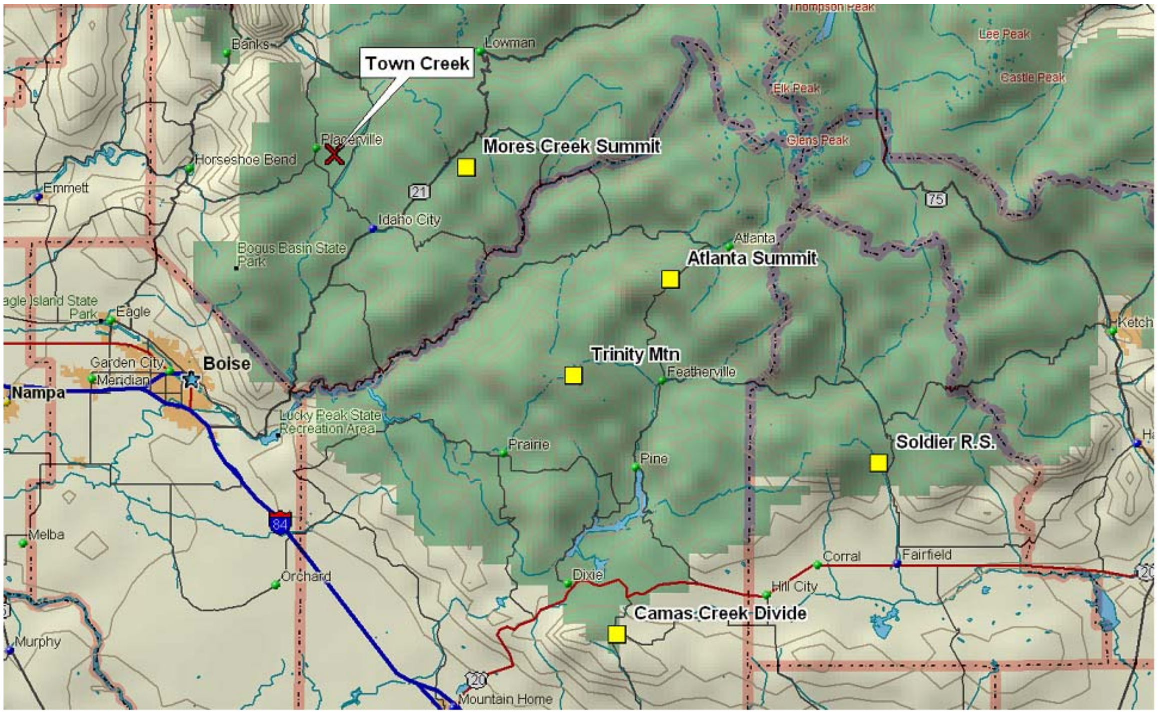

Figure 4.3 Locations of the NRCS Long-term Precipitation and Snowpack Observation Sites

Table 4-1 Average Monthly Precipitation at Five SNOTEL Sites

Site	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Oct.-Apr.	Water Year
Atlanta Sum.	2.5	6.3	6.5	6.8	4.9	5.9	2.9	35.8	44.2
Soldier R.S.	1.2	2.9	3.2	3.3	2.3	2.0	1.6	16.5	23.2
Mores Ck Sum.	2.2	6.8	6.9	7.7	5.7	4.8	3.1	37.2	45.7
Camas Ck Div	1.3	2.9	3.3	3.3	2.2	1.8	1.5	16.3	21.9
Trinity Mtn	2.6	8.3	8.7	8.5	7.0	5.2	3.3	43.6	52.7

Table 4-2 First of the Month Average Cumulative Snow Water Content at Five SNOTEL Sites

Site	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
Atlanta Sum.	0.0	1.4	7.0	13.4	20.1	26.2	31.9	31.1
Soldier R.S.	0.0	0.3	2.3	5.8	9.2	12.0	10.0	0.0
Mores Ck Sum.	0.0	0.8	6.3	13.7	21.7	29.2	34.6	31.0
Camas Ck Div.	0.0	0.0	1.6	5.1	9.3	11.7	11.0	3.0
Trinity Mtn.	0.0	2.0	9.1	17.0	25.5	33.4	39.5	40.5

Table 4-3 Seasonal Distribution of Precipitation at Five SNOTEL Sites

Site	Oct. – Apr. Precip. (inches)	Water Year Precip. (inches)	% Oct.- Apr vs. Water Year
Atlanta Sum.	35.8	44.2	81%
Camas Ck Div	16.3	21.9	74%
Mores Ck Sum	37.2	45.7	81%
Soldier R.S.	16.5	23.2	71%
Trinity Mtn	43.6	52.7	83%

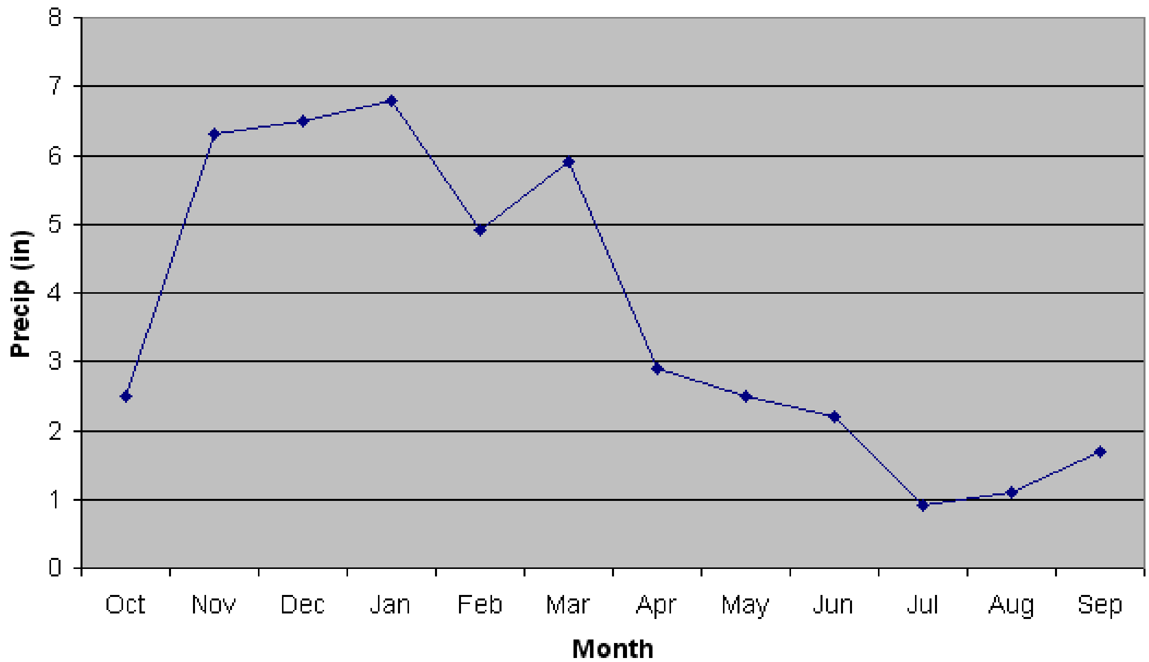

Figure 4.4 Average Monthly Precipitation, Atlanta Summit SNOTEL Site

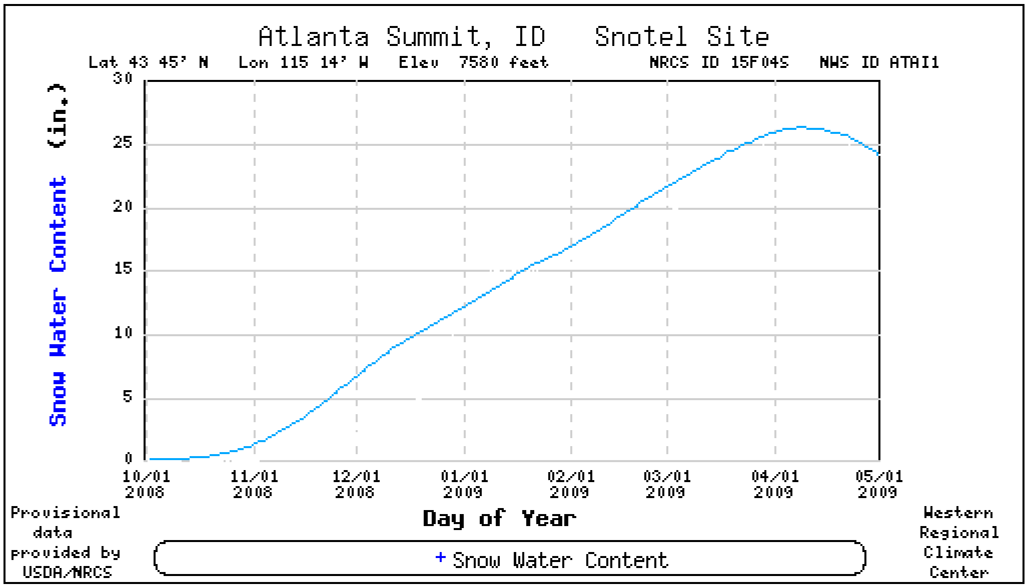

Figure 4.5 Average Winter Snow Water Content Accumulation, Atlanta Summit SNOTEL Site

Data from the above tables and figures indicate the following:

- Though precipitation occurs during the month of October, there is little snowpack accumulation during the month of October.
- The peak monthly precipitation amounts occur primarily during the three-month period of November, December, and January.
- Significant precipitation also occurs during the months of October, March and April.
- The highest precipitation and snow water accumulations for the winter season generally occur at the highest elevations in the target area.
- On average, the maximum snow water accumulations occur a little before April 1st at lower elevation sites and a little after April 1st at higher elevation sites.
- Approximately 70-85% of the target area precipitation occurs in the fall, winter and spring months of October through April.

4.2 Temperature

The temperatures observed in the proposed target area during the winter are a function of a number of factors including elevation, time of year, cloud cover, and the origin and type of air masses present over this area at a given time. Normally, temperatures in the free atmosphere decrease ~ 2.7^0 F (1.5^0 C) per 1000 foot rise in altitude. Figure 4.6 provides average maximum and minimum temperatures for the Atlanta Summit SNOTEL site. These average values are of general interest but the temperatures of special importance are those associated with the winter storm periods that impact the proposed target area. Climatological information specific to stormy weather periods will be provided in the following section.

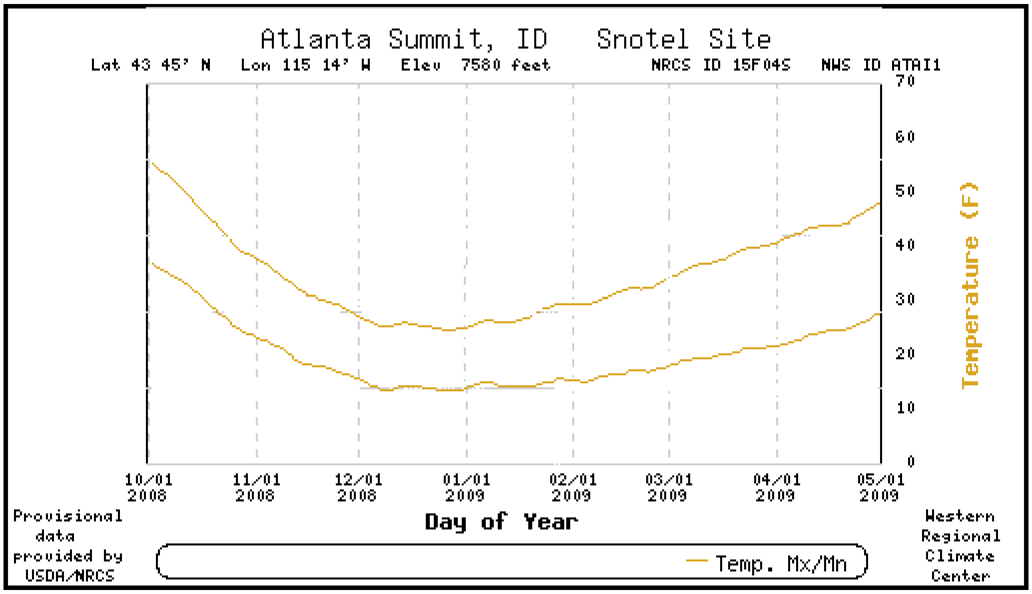

Figure 4.6 Average Winter Season Max/Min Temperature (^{0}F) at Atlanta Summit SNOTEL Site

4.3 Specialized (Storm Period-Specific) Climatological Information

A detailed analysis of storm periods affecting the target area was conducted for an eight-season period (water years 2001-2008) for the October-April season. Precipitation data from several SNOTEL sites were considered, and six-hour time blocks were selected when precipitation was clearly occurring in the target area. Data were examined from three SNOTEL sites: Atlanta Summit, Soldier R.S., and Mores Creek Summit. The SNOTEL data ranged from hourly to six-hourly in resolution and were obtained from the Natural Resources Conservation Service (NRCS).

A total of 386, six-hour periods were selected for analysis, generally corresponding to precipitation at the SNOTEL sites averaging more than about 0.1" and generally with precipitation evident in the data for at least two of the sites. These six-hour periods were matched as closely as possible to Boise weather balloon soundings, which we believe provide a good representation of this area. These soundings were used to derive temperature and wind data at the 700-mb and 500-mb levels, which are at approximately 10,000 and 18,000 feet MSL. The soundings also provided moisture (dewpoint) values, and a general idea of low to mid-level atmospheric stability. Estimates of the -5^0 C isotherm height and cloud-top temperature were also obtained from these sounding profiles.

4.3.1 Precipitation

A plot of the total number of six-hour storm periods analyzed by month is provided in Figure 4.7. This figure indicates that the month of December is the stormiest, on average.

Figure 4.8 provides the number of six-hour periods in the analysis (by month) for four different ranges of precipitation amounts in inches (0.10-0.19, 0.20-0.29, 0.30-0.39 and 0.40 or greater). The highest frequency is in the 0.20-0.29 range. This suggests that the precipitation rates are usually rather light, a common feature of winter storms in many of the mountainous areas of the Intermountain West.

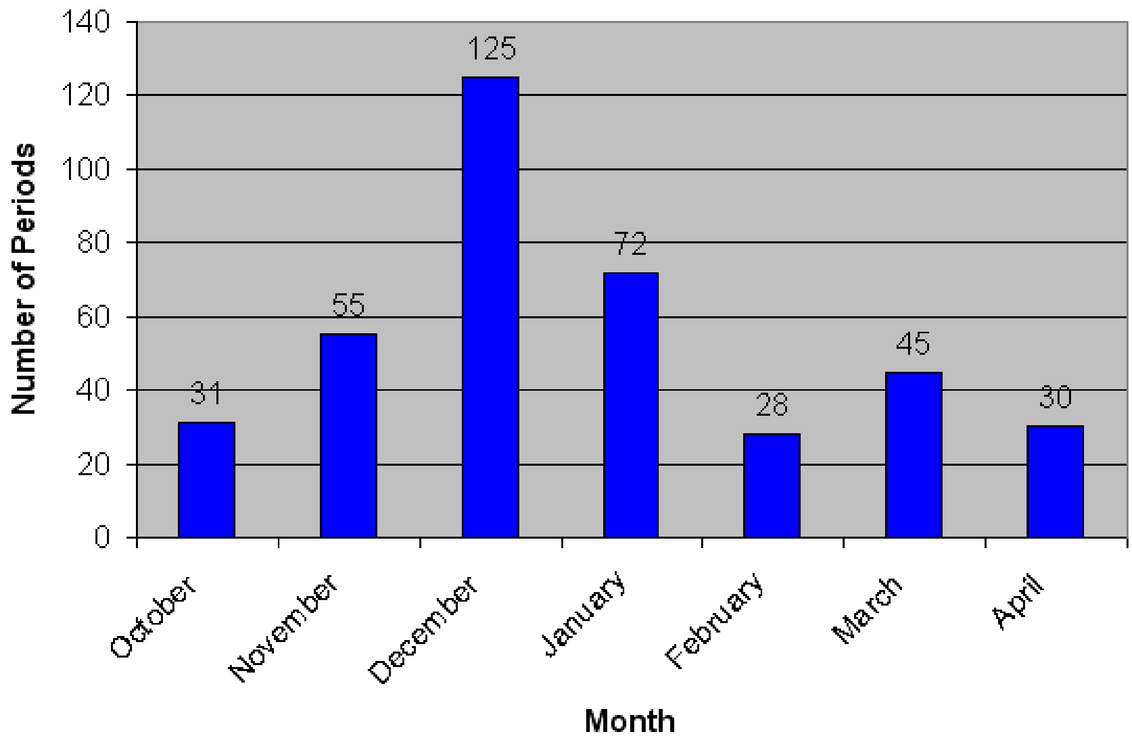

Figure 4.7 Frequency of 6-hour Storm Events by Month

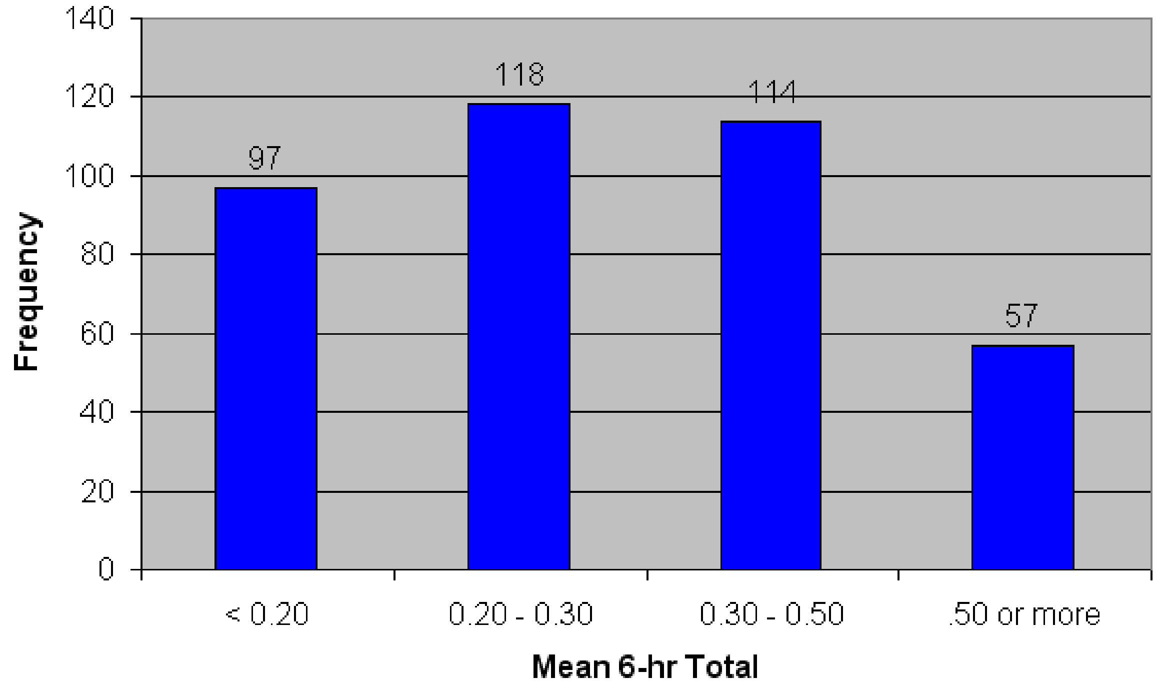

Figure 4.8 Frequency of 6-hour Storm Events by Precipitation Amount

4.3.2 700-mb Winds

NAWC has utilized the 700 mb level (approximately 9,500 feet MSL) as an index of important meteorological features regarding targeting of the seeding effects. First, the 700 mb wind is considered a good steering winds indicator, i.e., an approximation of the direction along which storm elements will move. NAWC has also used this level as guidance in the selection of ground -based generator sites. The 700 mb wind directions and speeds for the 6-hourly, eight-season sample described above were used to generate wind roses that graphically display the average information for each of three potential seeding modes: 1) lower elevation, ground based generators, 2) higher elevation remotely operated ground generators, and 3) airborne seeding. Discussions of these three seeding modes were provided in Section 3.6. Section 6.2.1 describes the analyses that were conducted to determine which storm events were considered to be seedable by the three different seeding modes. The wind roses provide the frequency of wind direction and speeds by 22.5 ^{0} wind sectors. Recall that wind directions in meteorology are reported according to the direction <u>from which</u> the wind is blowing. For example, a wind direction of 270 ^{0} means the wind is blowing directly out of the west towards the east. The velocities on these wind roses are plotted in knots. Figures 4.9 through 4.11 provide the storm period-specific wind roses for the three potential seeding modes. This information is used in a later section in discussions concerning the potential siting of ground generators and aircraft seeding tracks.

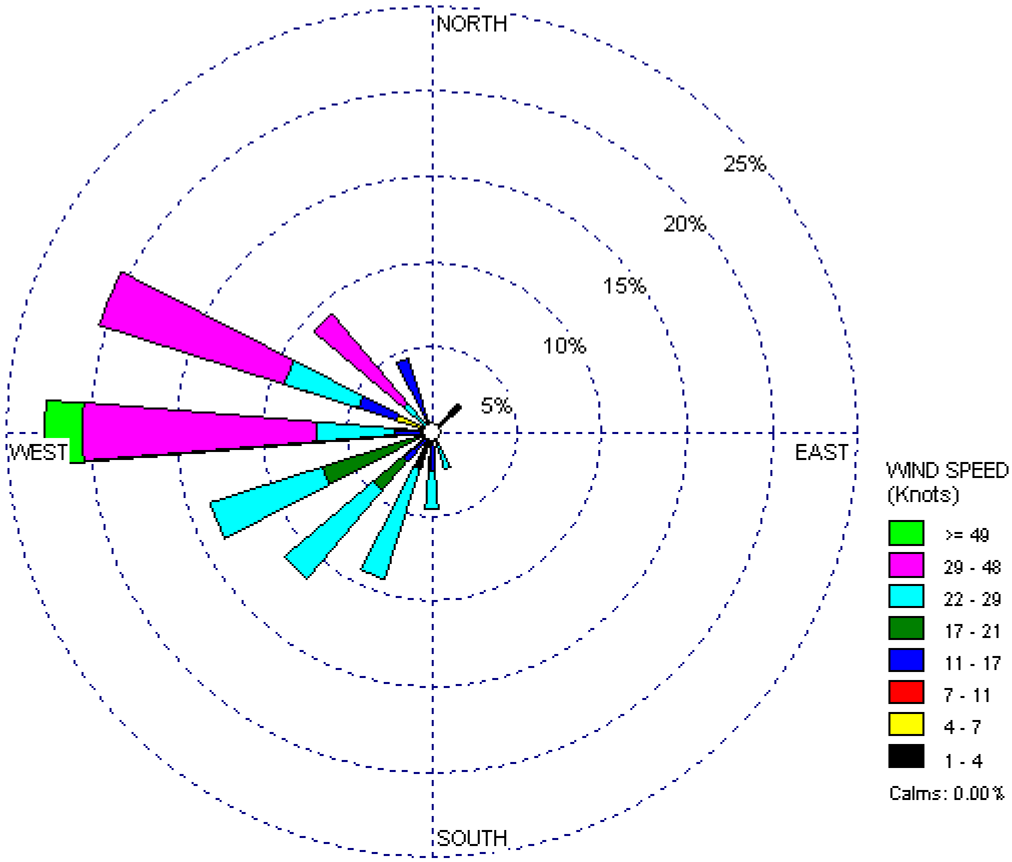

Figure 4.9   700-mb Wind Rose for Ground-based Seedable Events

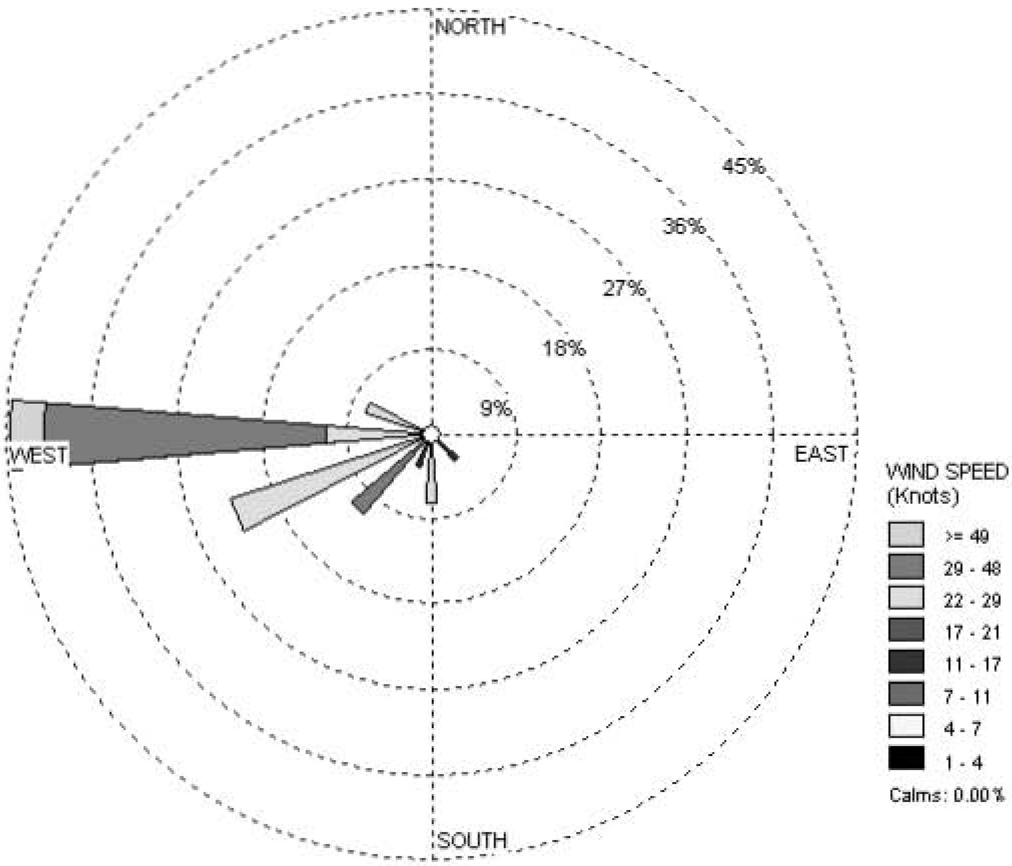

Figure 4.10 700-mb Wind Rose for Remote Generator Seedable Events

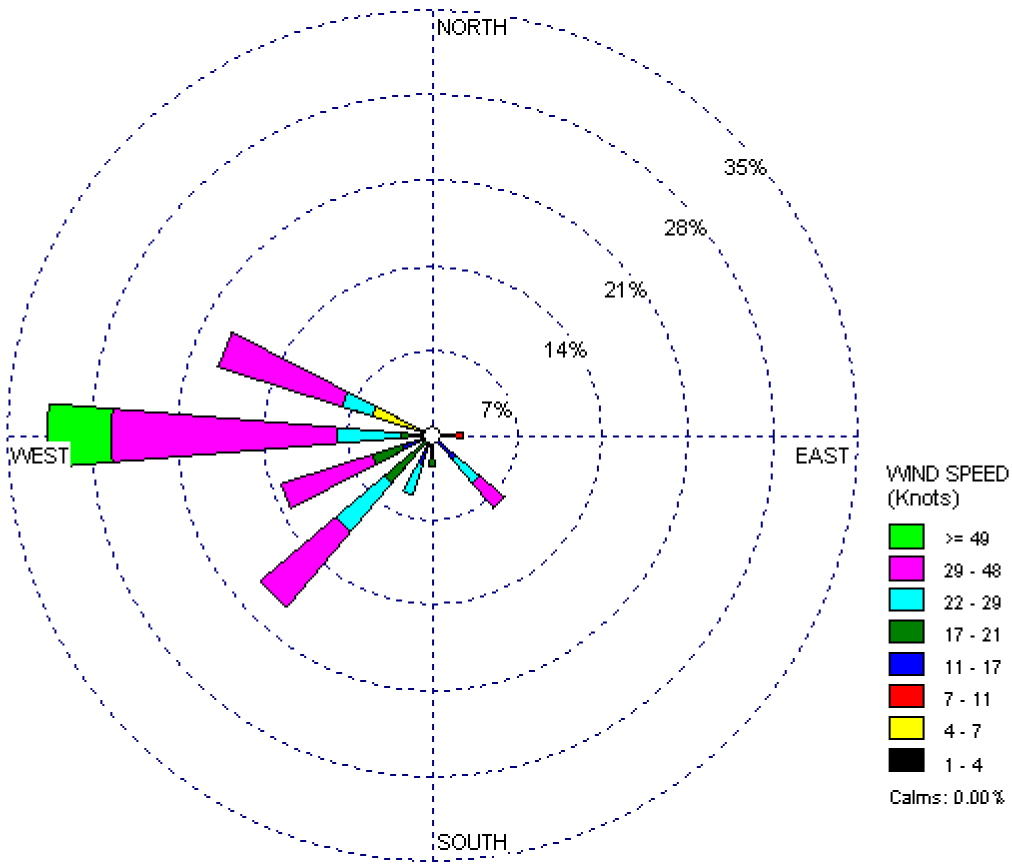

Figure 4.11 700-mb Wind Rose for Aircraft-only Seedable Events

4.3.3 700-mb Temperatures

A plot of the average 700-mb temperatures during the six-hour precipitation periods by month was prepared (Figure 4.12). We use temperatures at this level in helping decide whether a specific storm period is considered seedable using ground-based generators, since the 700-mb level is typically near the height of the target mountain barriers. Seeding materials released from ground generators have been shown to rise to approximately 1000-2000 feet (300-600 m) above the mountain crest heights. Silver iodide becomes an active ice nucleant at temperatures of about -4 to -5^0 C or colder. These factors indicate that the 700-mb temperature should be approximately -5^0 C or colder in order for seeding to be effective. The seeding material must have the opportunity to form ice crystals upwind of the barrier, which can then grow into snowflakes and fall onto the barrier. Figure 4.12 indicates that 700-mb temperatures did, in general, average $–5^0$ C or colder during the precipitation events. The month of October was on the marginal (warm) side. Figure 4.13 is a plot of the mean height of the 700-mb temperature by precipitation intensity, and Figure 4.14 is a corresponding plot of the -5^0 C isotherm by precipitation intensity (based on 6-hour precipitation amounts). These figures demonstrate that, on average, the -5^0 C isotherm is slightly higher during periods of greater precipitation intensity. This makes sense meteorologically because warmer air masses can hold more water, which can be converted into more snowfall, under the right conditions, than possible with colder storms.

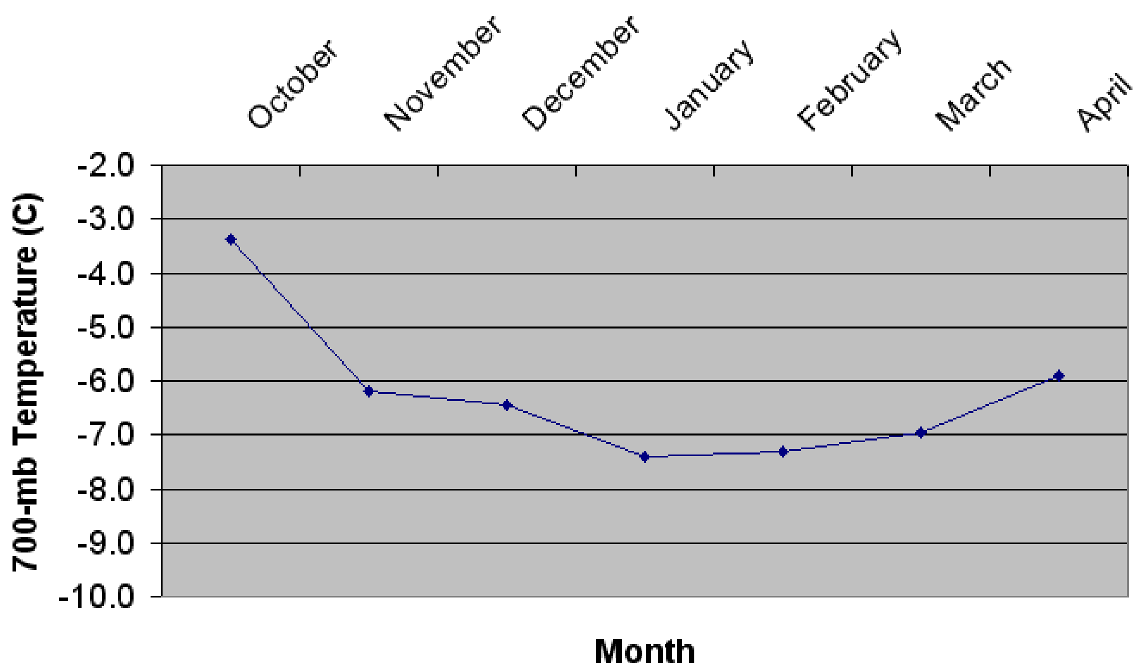

Figure 4.12 Mean 700-mb Temperature during Storm Periods by Month

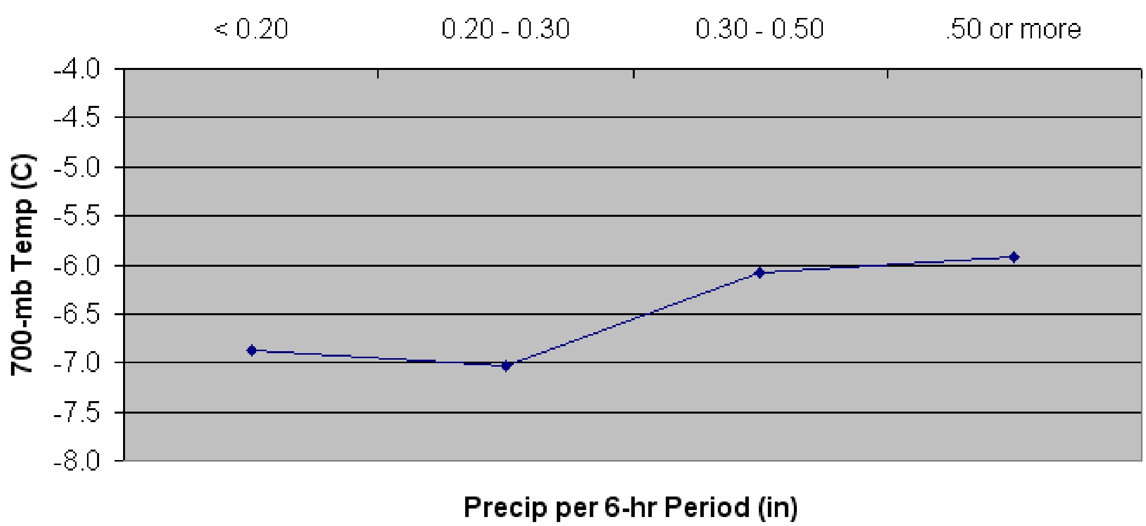

Figure 4.13 Mean 700-mb Temperature by Precipitation Rate

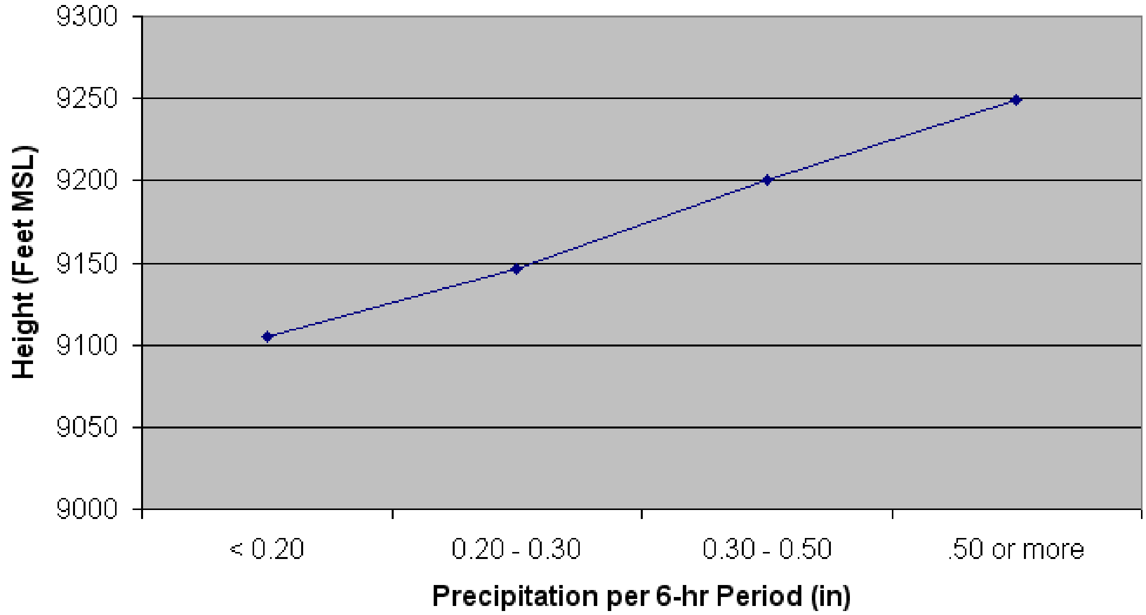

Figure 4.14 Mean Height of the -5^{0}C Isotherm by Precipitation Rate

4.3.4 Low-Level Stability

Another meteorological feature of special interest when considering ground-based cloud seeding is the frequency of occurrence of low-level temperature inversions in the atmosphere that may restrict the vertical transport of seeding materials released from the ground into seedable cloud regions. Temperatures in the atmosphere typically decrease with height. An inversion is said to exist if there is a layer in the atmosphere in which the temperature increases instead of decreases with height. Such inversions are responsible for the trapping of pollutants and formation of smog in mountain-valley areas (the Los Angeles Basin is an extreme example).

We performed an analysis to examine whether this phenomenon would potentially present a problem in seeding from ground generators in the UBRB. For this analysis, atmospheric stability (between the surface and 700 mb) was determined for the Six-hour precipitation events based upon the Boise rawinsonde observations. Surface temperature, wind and dewpoint observations were also utilized in conjunction with the Boise sounding profiles to obtain better estimates of low-level stability issues and wind patterns. After examination of the availability and quality of surface data, one site was utilized. This site was the Town Creek (4500') site northwest of Idaho City (location provided in Figure 4.3. These data were obtained from the Mesowest observation network, managed by the University of Utah Department of Meteorology.

Low-level stability (which could prevent seeding material from reaching the -5^0 C level over the target area) was classified into four categories: Well-mixed or neutral conditions (no stability problems evident, which should mean that silver iodide particles released near the surface should be transported over the mountain barriers in the storm winds), slightly stable, moderately stable, and very stable. These categories correspond roughly to situations when less than 2^0 C of surface heating would be necessary to mix out the atmosphere (slightly stable), $2\text{-}4^0$ C (moderately stable), and more than 4^0 C (very stable). Cases that were well mixed or slightly stable were considered suitable for lower elevation ground-based seeding, while more stable cases would require remote high-elevation ground generators or aircraft seeding.

The more-stable situations are cases where lower elevation ground-based seeding would probably not be attempted due to stability considerations. Figure 4.15 is a plot of the frequency of "neutral" stability below 700 mb for the seedable periods. Seedable periods are defined as those storm events that have estimated cloud top temperatures between -5^0 and -25^0 C (the importance of this criteria is discussed in section 6.2.1). As shown in the figure, the most favorable category of stability (neutral) averages about 28% of the seedable cases during the October - April (and November - April) period, and is only about 21% of all seedable cases when considering only the November - March period. This analysis suggests that low-level stability presents significant problems during the winter months. These are the months that have the highest average amounts of precipitation.

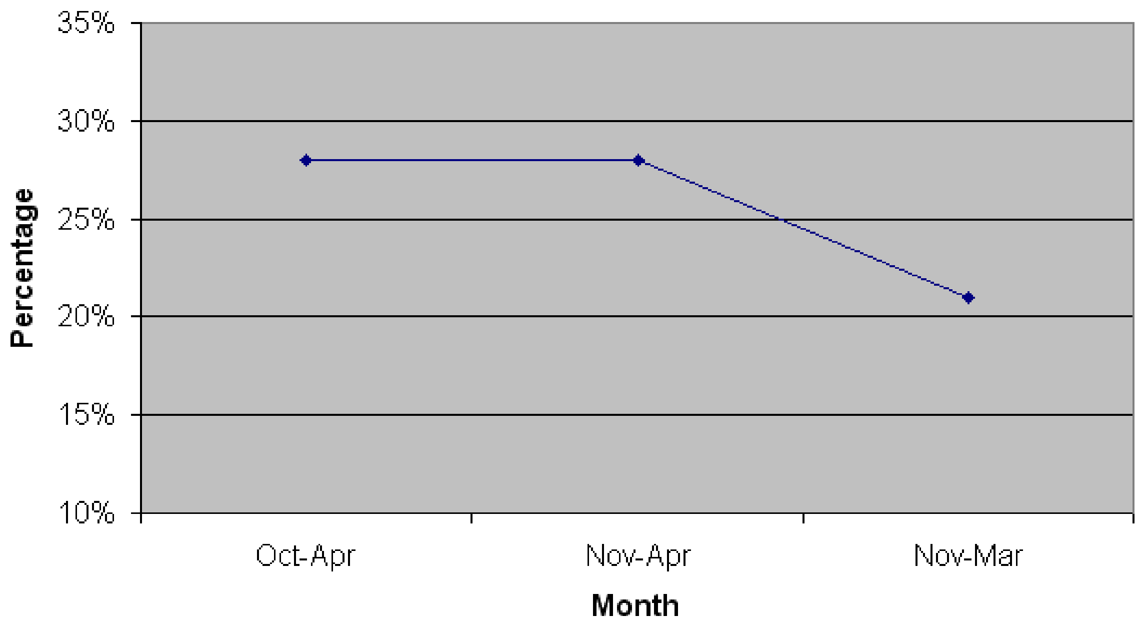

Figure 4.15 **Percentage of Seedable periods (defined by cloud top temperature between -5^0 to -25^0 C) with a "Neutral" Stability Profile by Different Time Periods**

5.0 REVIEW AND ASSESSMENT OF THE EXISTING PROGRAM (TASK 2)

Weather modification activities for the Boise Project Board of Control (BPBC) began during the winter season of 1992-93 prompted by drought conditions, which had been fairly persistent throughout the western United States for several years. North American Weather Consultants (NAWC) conducted this program for four consecutive winter seasons (1992-1996). It was discontinued for the next five seasons (1997-2001) due to adequate water supplies from natural precipitation. The program was conducted again for another four seasons from 2001-2005, and after being discontinued during the 2005-2007 period, was conducted again during the past two seasons (2007-2008 and 2008-2009). The target area encompasses the drainage of the Boise River above Anderson and Lucky Peak Reservoir in parts of Boise, Elmore and Camas Counties. The target area covers approximately 3,500 square miles of mountainous terrain and ranges in elevation from around 3,000 to 4,000 feet on its western side to just over 10,000 feet on its eastern side. Several peaks over 9,000 feet are located in the central and eastern parts of the target. The program has the goal of augmenting the snowpack that accumulates in those drainages. Benefits from the program are derived from increased hydropower production (Lucky Peak and Anderson Ranch Dams), enhanced streamflow used for irrigated agriculture, and underground aquifer recharge. There are a number of secondary benefits as well (e.g., recreational, forest ecology, etc.). The program design, assessment of program effectiveness and estimates of increases in streamflow are contained in the following sections. This information is taken from NAWC's most recent annual report on this program (Griffith, et al, 2009).

5.1 Program Design

5.1.1 Background

The Boise seeding program operational procedures have continued to utilize the basic principles of cloud seeding technology that have been shown to be effective during more than 30 years of wintertime cloud seeding in the intermountain west, particularly in the mountainous areas of Utah. Refinements have been incorporated as appropriate, and the operational treatment procedures adjusted for local topography and weather patterns. Evaluation results for these operational seeding programs have consistently indicated increases in wintertime precipitation during the periods in which cloud seeding was conducted. In the majority of the seeded water years the seasonal increases in precipitation have ranged from 5-15% more than mathematical regression analysis indicated would have occurred without seeding, for most of the Utah seeding target areas (Griffith, et al, 2009).

5.1.2 Seedability Criteria

Program operations have utilized a selective seeding methodology, which has proven to be the most efficient method and has provided the most beneficial results. Selective seeding, which targets only storms (or portions of storms) in which natural precipitation has at least reasonable potential for enhancement, is based on several criteria which determine the "seedability" of the storm. These criteria deal with the meteorological characteristics of the air mass and of the cloud mass (temperature, stability, wind flow and moisture content). Table 5-1 provides the seeding criteria, which NAWC has utilized for a number of years for this and other similar winter seeding programs.

Seeding cannot be effective unless the seeding material reaches portions of clouds at or colder than the warmest activation temperature (near -5^0C) for silver iodide. However, this will generally be accomplished if the cloud base is at a lower elevation than the mountain crest and no temperature inversions exist between the elevation of the cloud seeding generator and the cloud base. In relation to cloud seeding, the existence of a low-level temperature inversion means the atmosphere is very stable and, as a result, the silver iodide particles released from the ground based sources will likely not be carried aloft into the storm clouds.

Table 5-1
NAWC Winter Cloud Seeding Criteria

1)	CLOUD BASES ARE BELOW THE MOUNTAIN BARRIER CREST.
2)	LOW-LEVEL WIND DIRECTIONS AND SPEEDS THAT WOULD FAVOR THE MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THEIR RELEASE POINTS INTO THE INTENDED TARGET AREA.
3)	NO LOW LEVEL ATMOSPHERIC INVERSIONS OR STABLE LAYERS THAT WOULD RESTRICT THE VERTICAL MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THE SURFACE TO AT LEAST THE -5°C (23°F) LEVEL OR COLDER.
4)	TEMPERATURE AT MOUNTAIN BARRIER CREST HEIGHT EXPECTED TO BE -5°C (23°F) OR COLDER.
5)	TEMPERATURE AT THE 700 MB LEVEL (APPROXIMATELY 10,000 FEET) EXPECTED TO BE WARMER THAN -15°C (5°F).

5.1.3 Equipment and Program Set-Up

The Boise program has typically been operated for a five month period; either November 1st through March 31st or November 15th through April 15th. As a consequence, a NAWC field technician living in the Boise area installs the ground-based cloud seeding generators during October and early November. NAWC utilizes ground based, manually operated silver iodide generators on this program. Approximately 20 sites are installed for each winter's operations. The target area and seeding generator sites used during the 2008-2009 winter season are shown in Figure 5.1.

The cloud seeding equipment at each site includes a cloud seeding generator unit and a propane gas supply. The seeding solution consists of three percent (by weight) silver iodide (AgI), complexed with very small portions of sodium iodide and para-dichlorobenzene in solution with acetone. It is necessary that the AgI crystals become active in the region in the cloud which contains supercooled liquid water sufficiently far upwind of the mountain crest so that the available supercooled liquid water can be effectively converted to ice crystals which will then grow to snowflake size and fall out of the cloud onto the mountain barrier. If the AgI crystals take too long to become active, or if the temperature upwind of the crest is too warm, the plume will pass from the generator through the formation zone and over the mountain crest without freezing the cloud drops in time to affect precipitation in the desired area. The seeding formulation is designed to minimize this problem by causing nucleation in the cloud as quickly as possible, particularly in the warmer part of the effective temperature range.

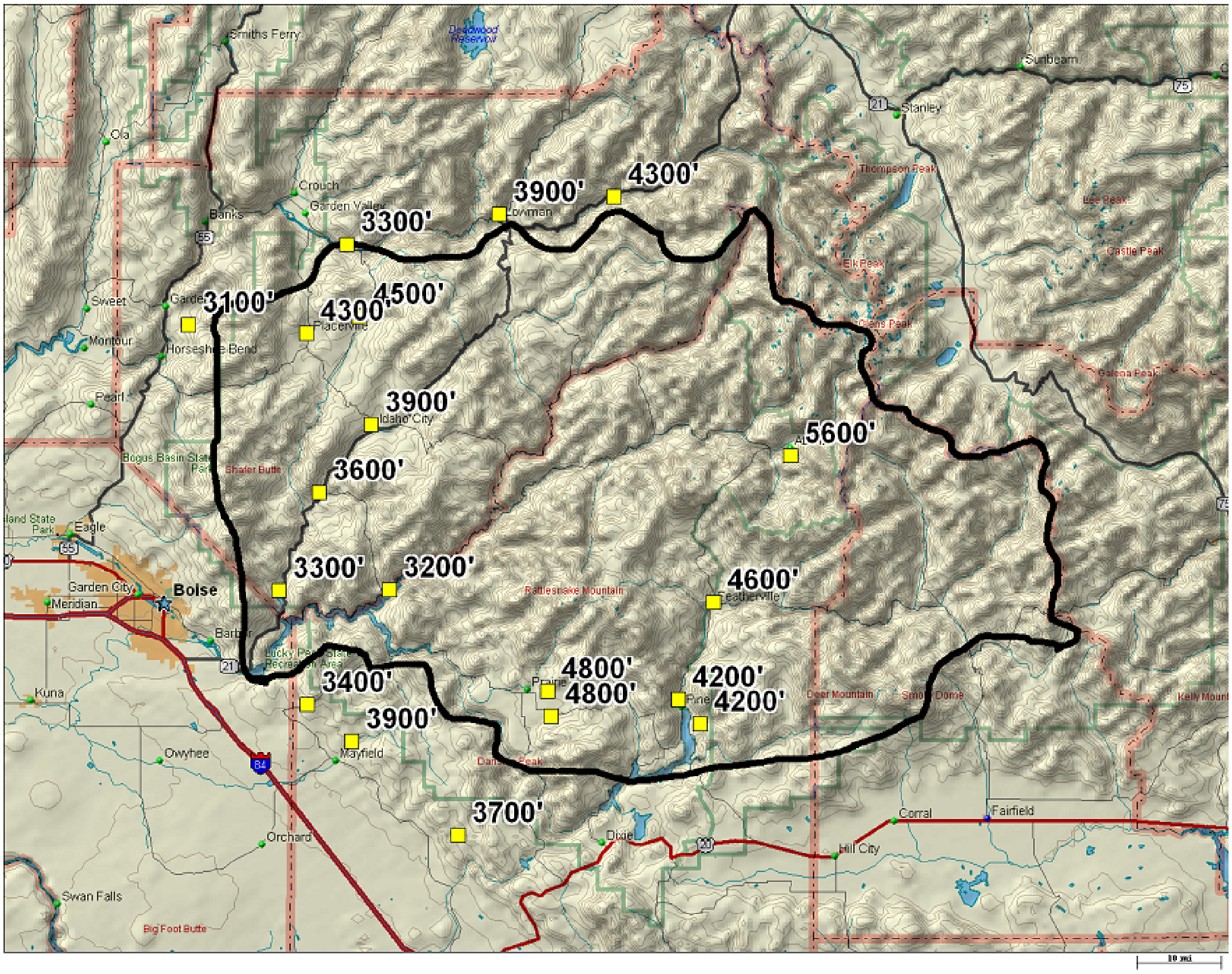

Figure 5.1 Target Area Outline and Ground Generator Locations, 2008-2009 Winter Season (elevations of the generator sites are indicated next to the yellow squares that denote the generator locations)

The seeding unit (see Fig. 5.2) is manually operated by igniting the propane flame (at the flame head in a burn chamber) and adjusting the flow of seeding solution through a flow rate meter. The propane gas also pressurizes the solution tank, which allows the solution to be forced into the burn chamber. The regulated seeding solution is sprayed through an atomizing nozzle into the propane flame, where microscopic silver iodide crystals are formed through the combustion process. These crystals, which closely resemble natural ice crystals in structure, are released at a rate of twelve grams per hour per generator when using a 3% solution of silver iodide.

The silver iodide crystals become active as artificial ice nuclei beginning at temperatures between -5^0 C and -10^0 C (23^0 to 14^0 F). Since experience has proven that seeding is most effective within a temperature "seeding window", the seeding generators were operated only during those periods when the temperatures within the cloud mass were expected to be between -5^0 C and -15^0 C (23^0 to 5^0 F).

Figure 5.2 Cloud Nuclei Generator (CNG)

Most storms that affect the Idaho Mountains are associated with synoptic (large-scale) weather systems that move into Idaho from the Pacific Ocean, either from the northwest, west, or southwest. Usually they consist of a frontal system and/or an upper trough, with the air preceding the front or trough flowing from the south or southwest toward the north or northeast. As the front/trough passes through the area, the wind flow changes to the west, northwest, or north. Thus, clouds and precipitation typically occur during windflow patterns ranging from southwesterly to northwesterly. For that reason, the seeding generators are situated to enable selective operation in southwesterly flow ahead of the front/trough and/or in the northwesterly flow following their passage, by placing them upwind of the mountains that comprise the target area.

5.1.4 Operations Center and Personnel

NAWC maintains a fully equipped program operations center at its Sandy, Utah headquarters. Real-time information is continuously acquired via the internet, allowing decisions to be made regarding whether, where and when to seed. Information acquired online includes surface weather observations, rawinsonde (weather balloon) observations, surface and upper air charts (both current and forecast), weather radar displays, weather satellite photographs, zone forecasts from the National Weather Service, as well as numerous other products. The program meteorologist in charge of the operations utilizes this information to make informed cloud seeding decisions, as well as documenting weather information and seeding activities for future reference. Figures 5.3 – 5.5 provide examples of the types of weather information available online utilized to make seeding decisions during the 2008-2009 season.

NAWC has a standing policy of operating within guidelines adopted to ensure public safety. Accordingly, NAWC has developed criteria and procedures for the suspension of cloud seeding operations if/when appropriate.

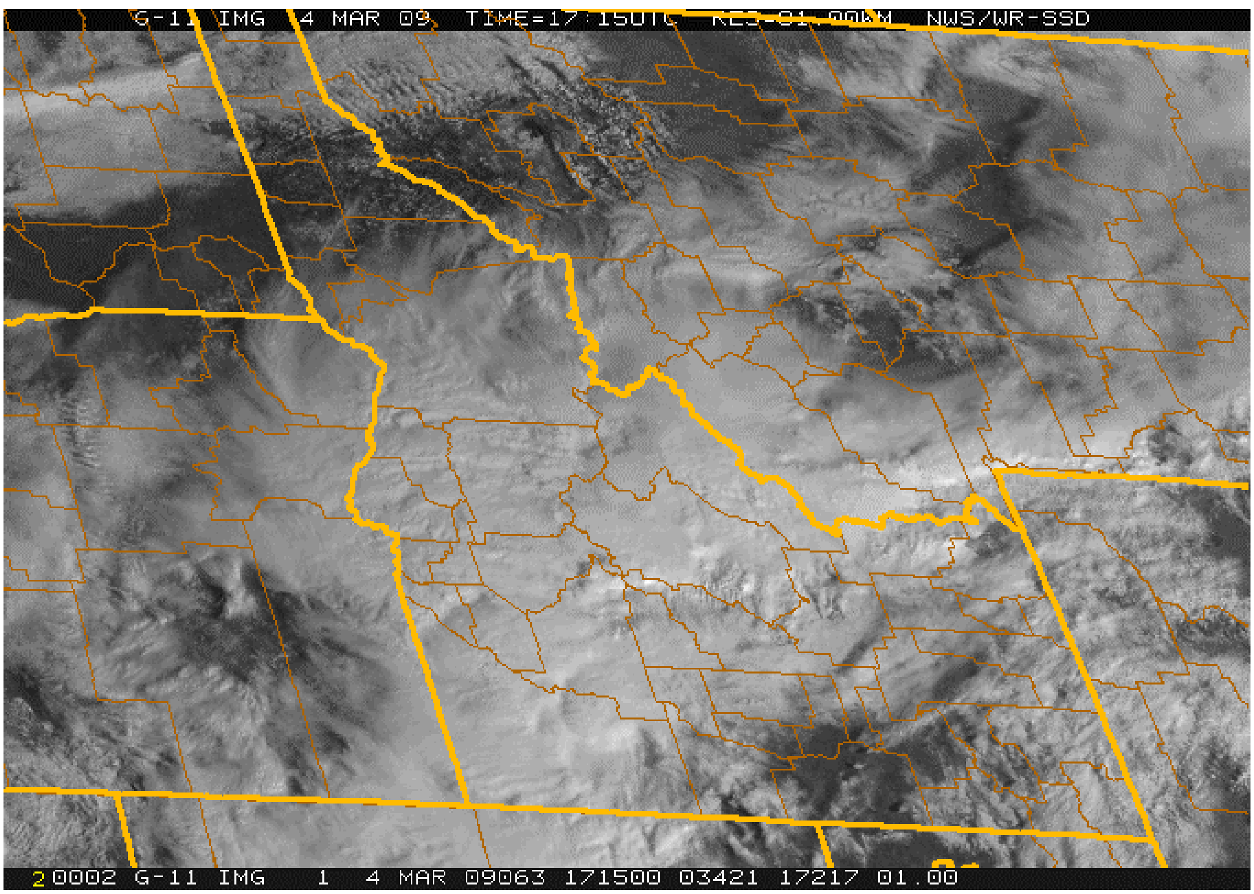

Figure 5.3 Visible Satellite Image on the Morning of March 4, 2009. (This image shows a heavy cloud deck, bright white area, covering much of Idaho).

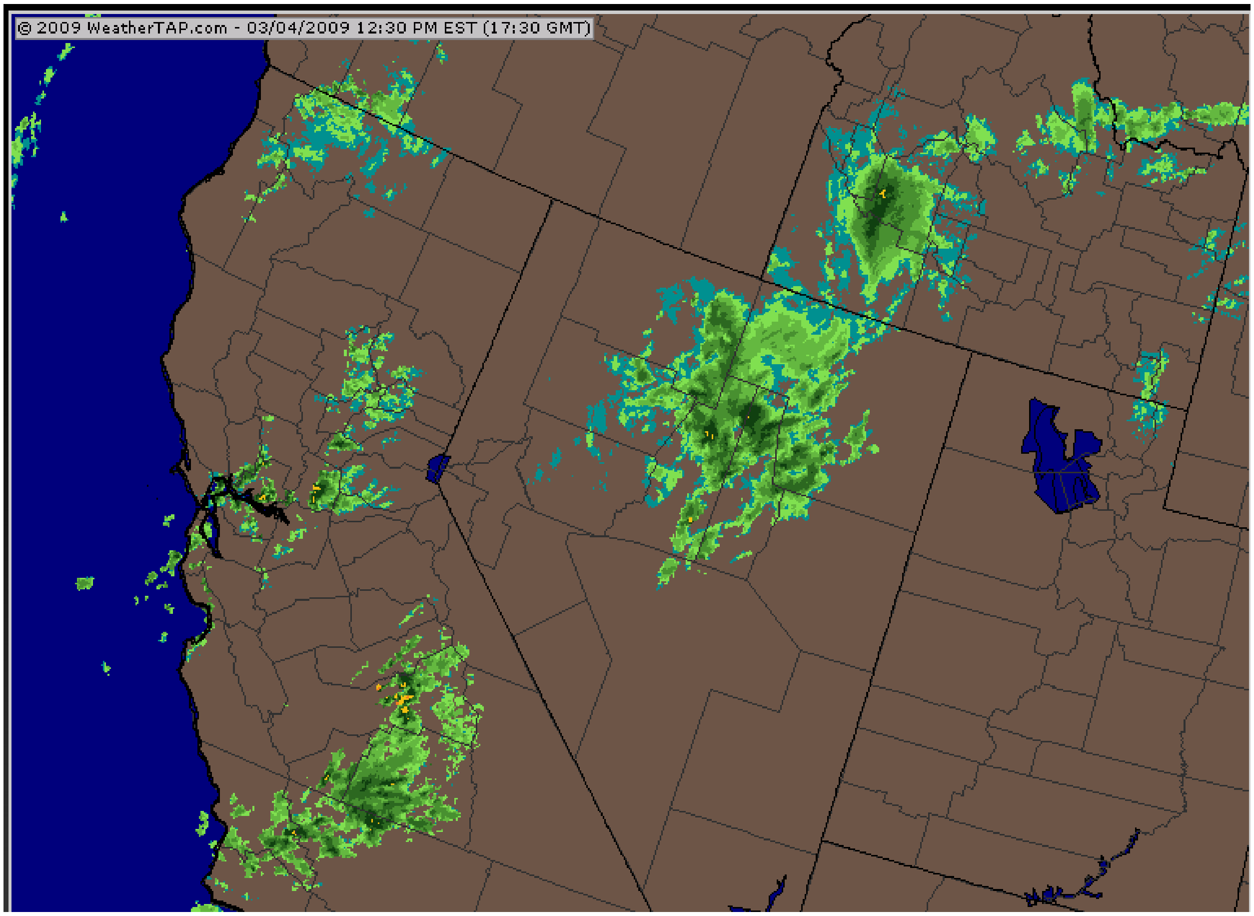

Figure 5.4 Regional Composite Weather Radar Image on March 4, 2009, near the time of the Satellite Image shown in Figure 5.3. (Although the radar beam is partially blocked over the target area, due to mountainous terrain, using radar images like this along with the satellite image is useful for identifying areas of significant precipitation).

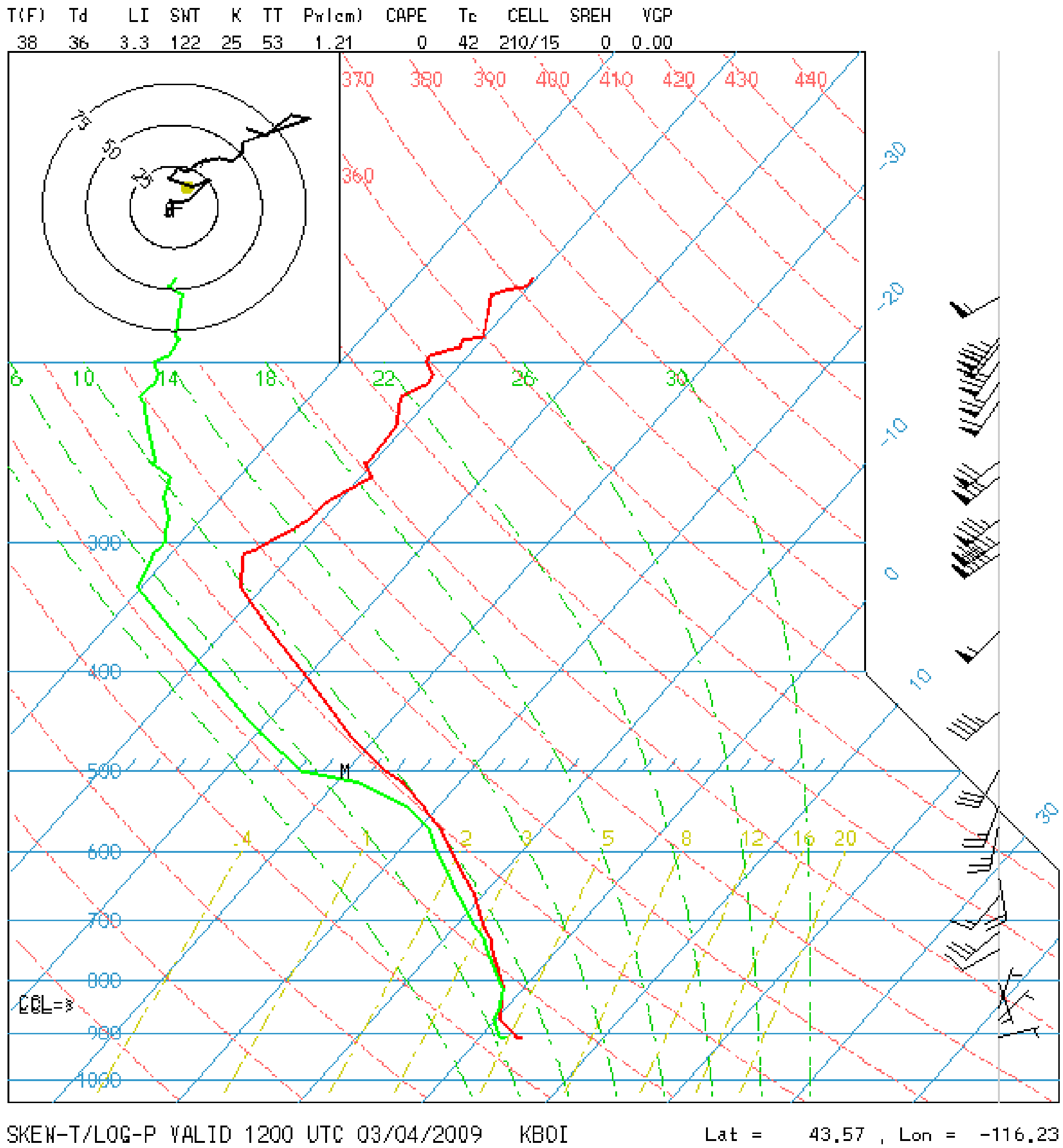

Figure 5.5 Upper-air Sounding (observed by a weather balloon) over Boise at 12Z (0500 MST) on March 4, 2009. (The right black line represents temperature, and the left black line is the dewpoint. Blue lines are pressure levels in millibars, horizontal and temperature in degrees C, diagonal. Wind barbs on the right show wind speed and direction at various levels. This sounding shows a 700-mb temperature near -8 C, with good moisture saturation in the lower and mid level of the atmosphere, green line in close proximity to red line. Winds are southwesterly at mid and upper levels, and somewhat variable in the lower levels).

5.2 Assessments of the Effectiveness of the Boise Program

5.2.1 Background

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, and the results should be viewed with appropriate caution. 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. 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 pattern. Larger seeding effects can be detected more easily, and with a smaller number of seeded cases, than are required to detect smaller increases.

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, being of the order of a 5-15 percent seasonal increase. In part, this relatively small percentage increase accounts for the significant number of seasons required to establish these results with any certainty, often five or more years.

Despite the difficulties involved, some techniques are available for estimation of the effects of operational seeding programs. These techniques are not as statistically rigorous or scientifically desirable as is the randomization technique used in research, where roughly half the sample of storm events is randomly left unseeded. Most of NAWC's clients do not wish to cut the potential benefits of a cloud seeding program in half in order to better document the effects of the cloud seeding program. The less rigorous techniques do, however, offer a reasonable indication of the long-term effects of seeding on operational programs.

A commonly employed technique, which is the one utilized by NAWC in this assessment and in evaluation of its other winter seeding programs, is an historical "target" and "control" comparison. This technique is one described by Dr. Arnett Dennis (1980) in his book entitled "Weather Modification by Cloud Seeding". The technique is based on selection of a variable that would be affected by seeding (such as liquid precipitation or snowpack). Records of the variable to be tested are acquired for an historical period of as many years duration as possible (20 years or more if available). These records are partitioned into those located within the designated "target" area of the program and those in a nearby "control" area or areas. Ideally the control sites should be selected in an area meteorologically similar to the target, but one which would be unaffected by the program seeding (or seeding from other adjacent programs). The historical data in both the target and control areas are taken from past years that have not been subject to cloud seeding activities. These data are evaluated for the same seasonal period of time (months) as that when the seeding is to be or has been conducted. The target and control sets of data for the unseeded seasons are used to develop an equation (typically a linear regression) which predicts the amount of target area precipitation, based on precipitation observed in the control area. This regression equation is then used during the seeded period to estimate what the target area precipitation would have been without seeding, based on that observed in the control area. This allows a comparison to be made 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 seeding activity.

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 geographically, and the more similar they are in terms of elevation, the higher the correlation. Control areas selected too close to the target, 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 subject variable (expected precipitation or snowpack) in the seeded years. An equation indicating perfect correlation would have an r value of 1.0.

Experience has shown that it is virtually impossible to provide a precise assessment of the effectiveness of cloud seeding over one or two winter-spring seasons. However, as the data sample size increases, it becomes possible to provide at least a reasonable estimate of seeding effectiveness.

5.2.2 Some General Considerations in the Development of Target/Control Evaluations

There have been, and continue to be, multiple cloud seeding programs conducted in the State of Idaho. As a consequence, potential control areas that are unaffected by cloud seeding are somewhat limited in geographic area. This is complicated by the fact that the best correlated control sites are generally those closest to the target area, and most measurement sites in this part of the state have been subjected to "contamination" by numerous historical and current seeding programs. This renders such sites of questionable value for use as control sites, since the actual impact from cloud seeding on a season-to-season basis is difficult to quantify.

To further complicate the matter, the number of sites (especially snow course sites) is continually being reduced. Even some cooperative observer sites, which are managed by the National Weather Service, have either been discontinued or become inactive at several locations.

There is one other consideration in the selection of control sites: potential downwind effects of other cloud seeding programs beyond the intended target area. Some earlier weather modification research programs have indicated that the precipitation can be modified in areas downwind of the intended target areas. Analyses of some of these programs have indicated increases in precipitation in these downwind areas out to distances of 50-100 miles. A few years ago, NAWC completed an analysis of the potential downwind effects of cloud seeding, utilizing a long-term program that has been conducted in central and southern Utah (Solak, et al, 2003). Historical regression equations were developed for that study to examine the possible existence of downwind effects. Figure 5.6, taken from this study, shows ratios of the actual over predicted precipitation for several precipitation sites in southeast Utah and southwest Colorado downwind of the seeding program target area (the target area is shown in this figure). This figure indicates possible positive downwind effects from this program out to locations near the Utah/ Colorado border, a distance of approximately 100 miles from the location of the seeding generator network. The downwind study therefore suggests that if we wish to consider any precipitation gage sites in central Idaho as control sites for the Boise program, they should be located at least 50-75 miles downwind of current or historic cloud seeding programs in Idaho to avoid significant contamination.

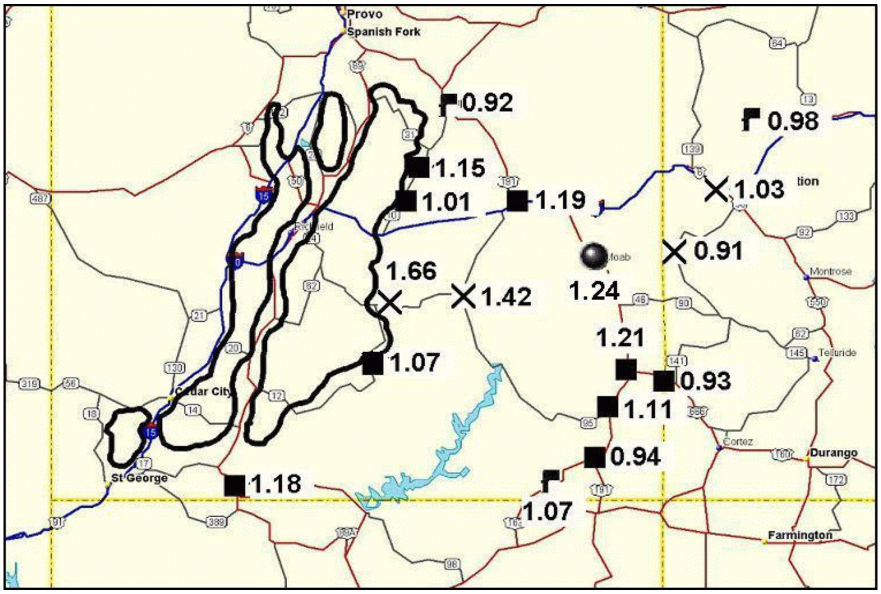

Figure 5.6 Ratios of Actual/Predicted Downwind Precipitation at Select Sites from Utah Study (target area enclosed by solid lines)

NAWC's normal approach in selecting control sites for a new program is to look for sites that will geographically bracket the intended target area. The reason for this approach is that we have observed that some winter seasons are dominated by one upper airflow pattern while other seasons are dominated by other flow patterns. The result of different upper airflow patterns often results in heavier precipitation in one area versus the other. For example, a strong El Nino pattern may favor a drier weather pattern in the northwestern United States, while a strong La Nina pattern may favor wetter weather in the northwestern U.S. and drier weather in the southwestern United States. Having control sites either side of the target area relative to the generalized flow pattern can improve the prediction of target area precipitation under these variable upper airflow pattern situations.

An additional consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control site may be rejected due to poor data quality, which usually manifests itself in terms of missing data. Fortunately, missing data (typically on a daily basis) are noted in the historical database so that sites can be excluded from consideration if they have much missing data. We normally drop a site if it has more than 2 or 3 days of missing data in a month for 4 or 5 months during the historical period we are considering, which could be a 15–30 year period. Data quality may appear to be satisfactory but another consideration is whether the station has been moved during its history. If a significant move (more than a mile or change in elevation of 100-200 feet) is indicated in the station records, then we may perform a double mass analysis of the station of interest versus another station in the vicinity with good records. The double mass plot (an engineering tool) will indicate any changes in relationships between the two stations. If these changes (deflections in the slope of the line connecting the points) are coincident with station moves and they suggest a significant difference in the relationship, the site is dropped from further consideration.

A final caution needs to be noted. That is concerned with the two types of precipitation observations typically available from mountainous areas in the west: standpipe storage precipitation gages and snowpillows. There are potential problems associated with each type of observation. With the advent of the Natural Resources Conservation Service's (NRCS) SNOTEL data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before the SNOTEL system was developed, these data had to be acquired by actually visiting the site to make measurements. This is still required at some sites. Figure 5.7 is a photo of an NRCS SNOTEL site taken in the fall, to allow the reader a better understanding of the two types of observation systems. The vertical tube is the standpipe storage gage, which is approximately 12" in diameter. The gages are approximately 20' in height so that their sampling orifices remain above the snowpack surface. As discussed in section 4, there are at least two types of problems associated with high elevation observations of the water equivalent of snowfall, as measured by standpipe precipitation storage gages. The two areas of concern are clogging at the top of the standpipe storage gage, and blow-by of snowflakes past the top of the standpipe gage. Either situation would result in an underestimate of the actual precipitation that fell during such periods. In the fall, the storage gage is charged with antifreeze, which melts the snow that falls to the bottom of the gage. A pressure transducer records the weight of the solution. The weight of the antifreeze is subtracted from the total weight, giving the weight of the water, which is then converted into inches. Heavy, wet snow may accumulate around the top of the standpipe storage gage, either reducing or stopping snow from falling into the standpipe and resulting in an underestimate of precipitation.

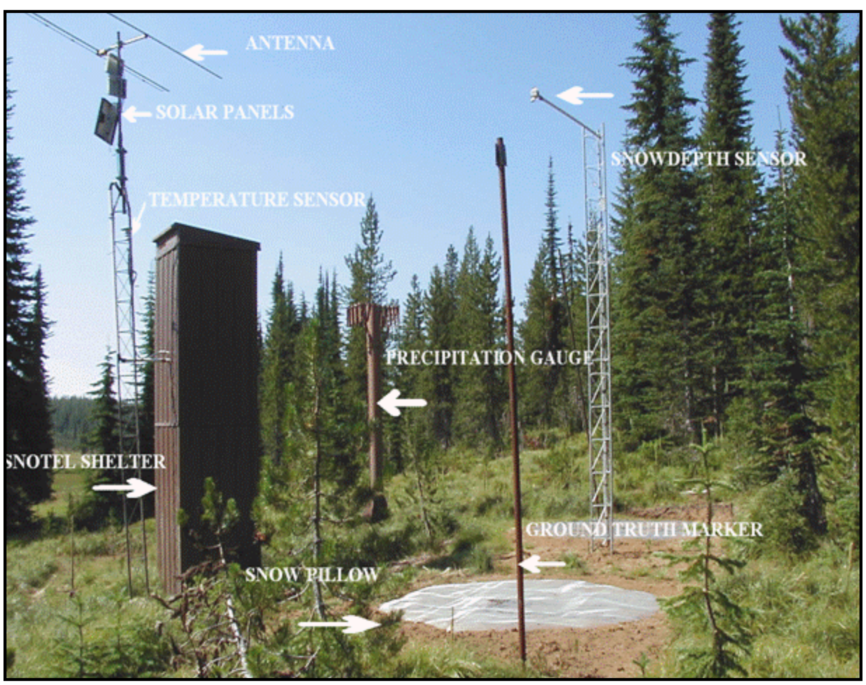

Figure 5.7 SNOTEL Site in the Fall

Snow that falls with moderate to strong winds may blow past the top of the gage, which can also result in an underestimate of precipitation. NRCS sites are normally located in small clearings in forested areas to help reduce the impacts of wind problems. Sites that are near or above timberline are more likely to be impacted by wind since sheltered sites may be difficult to find in these areas. The snow pillow, pictured on the pad at ground level in the foreground of Figure 5.7, is filled with antifreeze. This system weighs the snowpack, providing time-resolved records of the snowpack water content. Snow pillows can also have difficulty in providing accurate measurements of snow water content, because of wind either adding or removing snow from the measurement site when snow conditions are favorable for drifting.

The bottom line is that it is difficult to accurately measure snow water equivalent at unmanned high-elevation sites. Both types of NRCS observations (gage and snow pillow) can best be viewed as approximations of the actual amount of water that falls during a winter season. NRCS SNOTEL sites frequently provide the only type of precipitation observations available from the higher elevation areas that are targeted by winter cloud seeding programs. They are well suited for use in estimations of seeding effects, but interpretation of the indicated seeding effects must keep in mind the limitations of the measurement systems and their data.

5.2.3 Evaluation of Snowpack in the Target Area

Historically, the Natural Resources Conservation Service (NRCS), formally the Soil Conservation Service (SCS), routinely measured the mountain snowpack at snowcourses once or twice per month, usually starting in January and continuing until about June 1st. Measurements were made by visiting the snowcourse, where core samples of the snow were taken to determine the snow water content and snow depth. This is still being done at some sites. In more recent years, since about 1980, the advent of NRCS's SNOTEL system has allowed automated daily measurements of snow water and precipitation at many of the mountain sites. By use of a sensing system called a snow pillow, the water equivalent of the snowpack can be determined by remotely reading the weight of the snow on the snow pillow.

The water content within the snowpack is important since it ultimately determines how much water will be available when the snowmelt occurs. Hydrologists routinely use the water content to make forecasts of streamflow during the spring and early summer months.

Some problems inherent with snowpack measurements must be recognized when using snow water content to evaluate seeding effectiveness. One problem is that not all winter storms are cold, and sometimes rain as well as snow falls in the mountains. This can lead to disparity between a) precipitation totals, which measure everything that falls, and b) snow water content, which measures only the water contained in the snowpack at a given time. Also, warm periods can occur after snowstorms. If snow has fallen between the monthly snowcourse measurements and then a warm period occurs, some of the precipitation that fell as snow will have melted or sublimated by the time the next snowcourse measurement is made. This precipitation will never be recorded (even though some of the melted snow may have gone into the ground to recharge the soil moisture and ground water). This can lead to a greater disparity between snow water content at higher elevations (where less snow will melt in warm weather) than that at lower elevations.

April 1 snowpack readings have generally become accepted as the most representative data set since they usually represent the maximum snow accumulation for the winter season. Most streamflow and reservoir storage forecasts are made on the basis of the April 1 snowpack data. For that reason the April 1 snowpack data was selected for evaluation of seeding effects.

Snowpack (water equivalent) data used in the analysis were obtained from the NRCS and represent their official published records. Similar precipitation data used in the precipitation evaluation were also obtained from the NRCS, Western Region Climatic Center (WRCC), or from the National Climatic Data Center (NCDC).

It must also be noted here that there are two possible sets of data that can be used for the pre-SNOTEL period of sites that were converted from snowcourse to SNOTEL sites. This is because there are sometimes minor differences in the data obtained using the snowcourse and SNOTEL measurement systems. The NRCS may have determined, for example, that the SNOTEL snow water measurements were greater, on average, than snowcourse measurements made at a given site. The NRCS has published both actual snowcourse data measured at the time (during the pre-SNOTEL time period), as well as adjusted snowcourse data that were meant to be more consistent with the more recent SNOTEL data. This was accomplished (by the NRCS) utilizing a statistical examination of an overlap period (normally on the order of 10 seasons) for each measurement site, when both snowcourse and SNOTEL measurements were taken at that site. After careful consideration and examination of the NRCS data adjustments, NAWC decided in 2003 that use of the NRCS-adjusted data would yield a more consistent historical data set, that would less likely be biased by a change in measurement techniques (i.e., the switch to from snowcourse measurements to the automated SNOTEL system). This decision was made after the 2002-2003 seasonal report for the Boise River Basin was already completed, so the change was not reflected in that report.

Using the target-control comparison approach described above, mathematical relationships for the snowpack water content have been determined between a group of sites in an unseeded area (the control group) and the sites in the seeded area (the target group). From these data, a predictor equation was developed whereby the amount of the snowpack observed in the unseeded (control) area was used to predict the amount of natural snowpack in the seeded (target) area. The difference between the predicted (natural) amount and the observed amount in the seeded area (target) is the excess, which should approximate the result of the seeding.

5.2.3.1 Target Area Snowpack Sites

Figure 5.8 indicates that most of the snow target sites are located in the eastern two-thirds of the area outlined in the figure, which is the higher-elevation side of the target area. A number of NRCS snowcourse and snowpillow sites are located within this higher elevation region. Most of these sites are at elevations above 5,500 feet MSL, with over half of those selected as target area sites at elevations above 7,400 feet MSL. In total, nine sites were used in the 2008-2009 evaluation. This target group is the same as that was originally selected for the initial seeding program in 1992-93, minus a site at Camas Creek at which measurements were discontinued in 2000. The nine target sites are listed in Table 5-2 as sites 1-9, and are plotted in Figure 5.8, which also depicts the outline of the Boise River drainage. Five of the target gages are within the drainage, and two are located along the eastern edge of the drainage. Two other sites, numbers 4 and 5 (Galena and Galena Summit respectively), are included in the target area evaluation since they are located immediately downwind of the eastern target boundary and within the envelope of likely seeding effects. The average elevation of the target sites is 7,387 feet MSL.

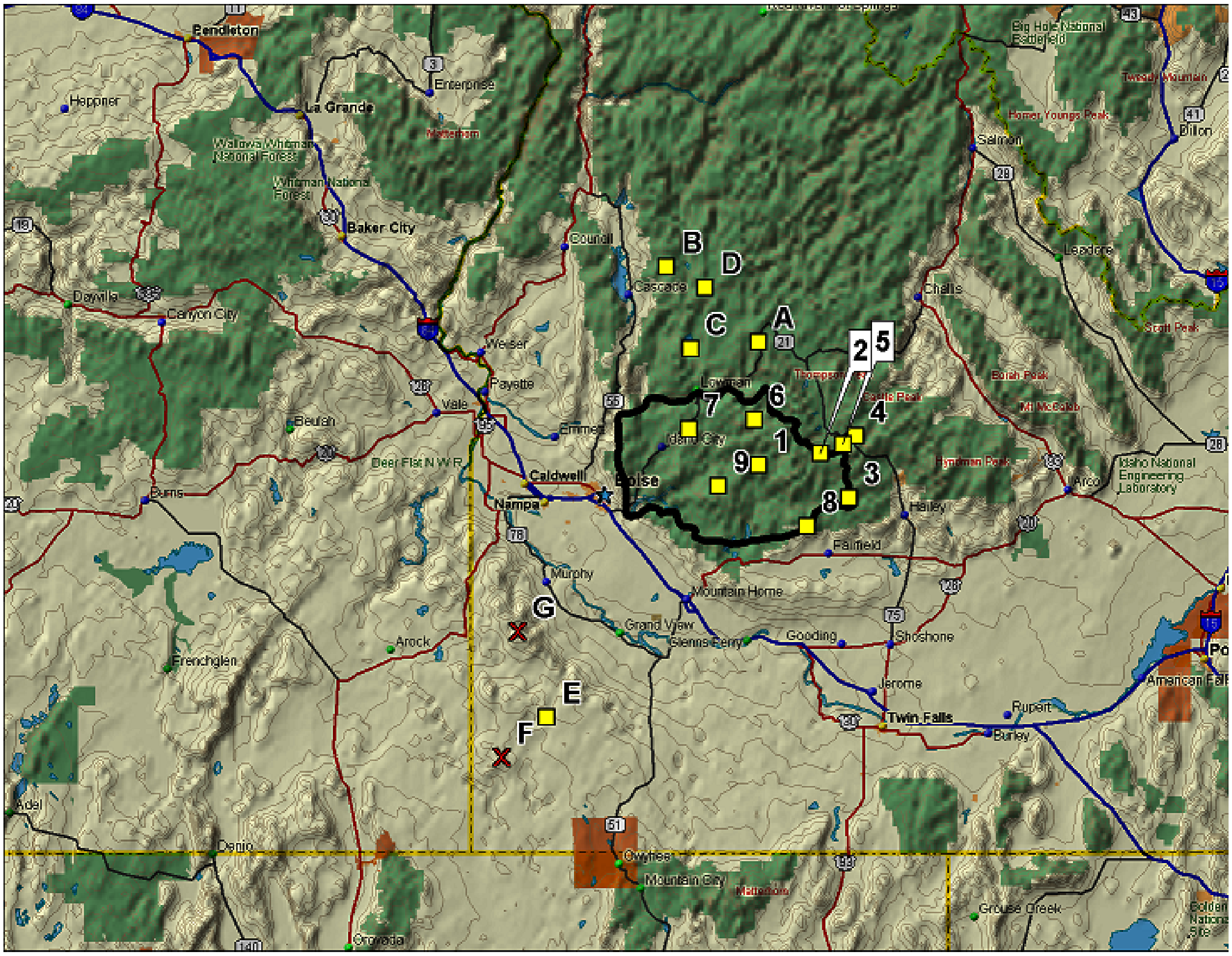

Figure 5.8 **Target Sites (numbers) and Original Control Sites (letters) used in Earlier Snowpack Evaluations. (Squares represent SNOTEL sites, and X's are snow courses; labels correspond to Tables 5-2 and 5-3)**

Table 5-2
Snowpack Target Sites

Map ID	Site Name	NRCS ID	Elev. (Ft)	Lat (N)	Long (W)
1	Atlanta Summit	15F04S	7580	43° 45'	115° 14'
2	Vienna Mine	14F04S	8960	43°48'	114°51'
3	Dollarhide	14F08S	8420	43° 36'	114° 40'
4	Galena	14F17S	7440	43° 53'	114° 40'
5	Galena Summit	14F12S	8780	43° 51'	114° 43'
6	Graham G.S.	15F14S	5690	43° 57'	115° 16'
7	Mores Creek Summit	15F01S	6100	43° 55'	115° 40'
8	Soldier R.S.	14F11S	5740	43° 29'	114° 49'
9	Trinity Mountain	15F05S	7770	43° 38'	115° 26'

5.2.3.2 Control Area Snowpack Sites

NAWC had established control sites to evaluate the Boise Program following the completion of the first winter of seeding (1992-93). Figure 5.8 (and Table 5-3) show the original set of controls. A seeding program was conducted during the past four winter seasons in the Payette River drainage, an adjacent basin to the north of the Boise River target area. This program, which is being conducted by Idaho Power, utilizes a seeding aircraft and a number of ground based silver iodide generators. Due to concerns about potential contamination of some of the control sites used in the previous evaluations, an alternate set of control sites was developed. This alternate set of control sites was established for the 2002-2003 evaluation. These sites were selected both to help reduce potential contamination of the data due to seeding in the Payette River Basin, and according to the following: 1) their correlation with the target area, 2) geographic bracketing of the target area, and 3) similarity to the target area in terms of elevation and meteorology. Figure 5.9 shows the set of control sites used in the 2008-2009 evaluation, as listed in Table 5-3. There is still the potential for some contamination from the Payette program affecting sites A, B and C. In addition, there is the potential for contamination from the Boise River program at sites H and I.

Table 5-3
Original Snowpack Control Sites (see Fig. 5.8)

Map ID	Site Name	NRCS ID	Elev. (Ft)	Lat. (N)	Long (W)
A	Banner Summit	15E11S	7040	44° 18'	115° 14'
B	Big Creek Sum	15E02S	6580	44° 38'	115° 48'

Map ID	Site Name	NRCS ID	Elev. (Ft)	Lat. (N)	Long (W)
C	Cozy Cove	15E08S	5380	44° 17'	115° 39'
D	Deadwood	15E04S	6860	44° 33'	115° 34'
E	Mud Flat	16G07S	5730	42° 36'	116° 33'
F	Red Canyon	16G11S	6650	42° 26'	116° 50'
G	Silver City	16F03S	6400	43° 00'	116° 44'

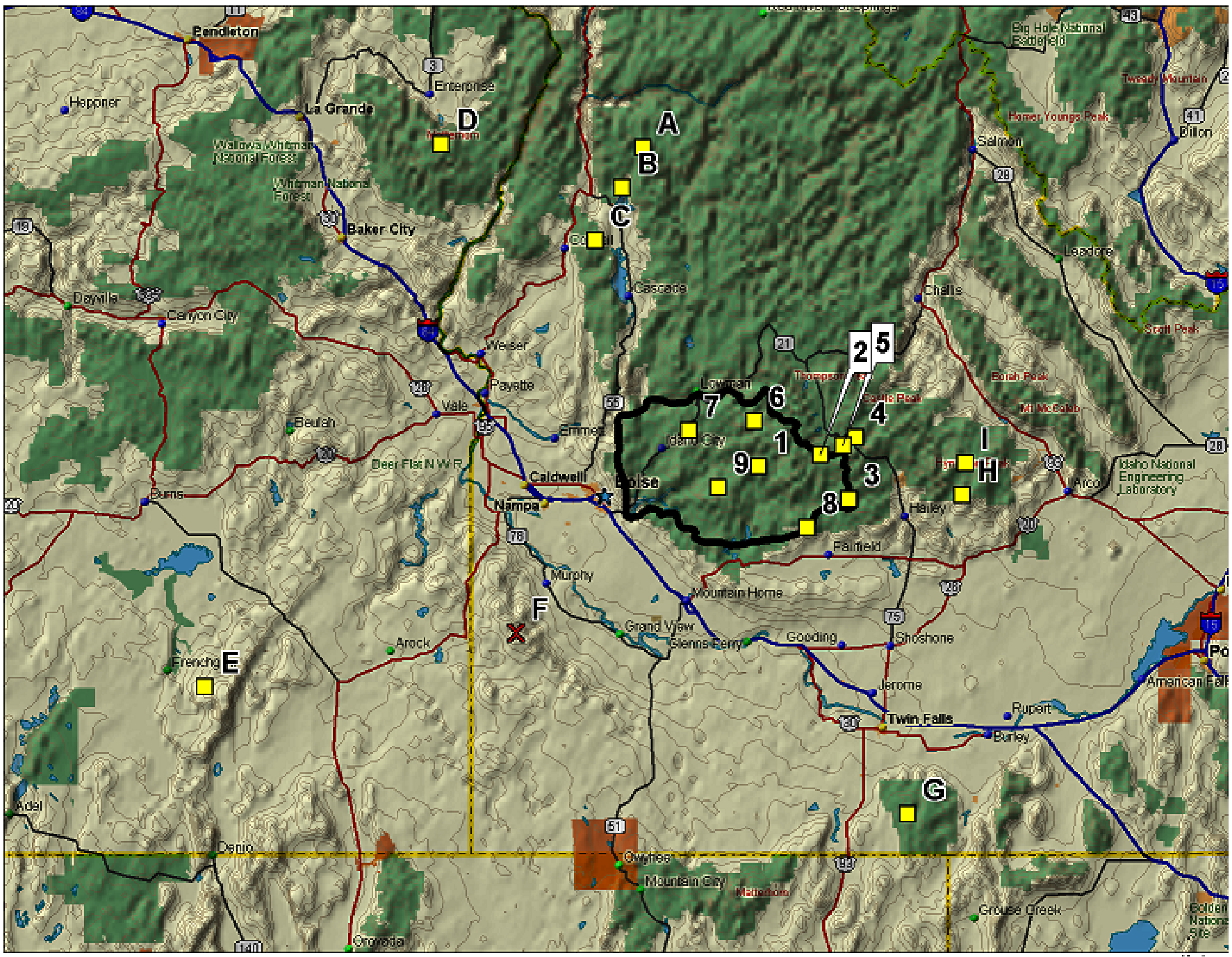

Figure 5.9 **Target Sites (numbers) and Alternate Control Sites (letters) used in Snowpack Evaluations. (Squares represent SNOTEL sites, and X's are snow course sites; labels correspond to Tables 5-2 and 5-4)**

Table 5-4
Alternate Snowpack Control Sites (see Fig. 5.9)

Map ID	Site Name	NRCS ID	Elev. (Ft)	Lat. (N)	Long (W)
A	Secesh Summit, ID	15D01S	6520	45°11'	115°58'
B	Brundage Res., ID	16D09S	6300	45°03'	116°08'
C	Squaw Flat, ID	16E05S	6240	44°46'	116°15'
D	Aneroid Lake #2, OR	17D02S	7300	45°13'	117°12'
E	Silvies, OR	18G01S	6900	42°45'	118°41'
F	Silver City, ID	16F03S	6400	43° 00'	116° 44'
G	Magic Mountain, ID	14G02S	6880	42°11'	114°18'
H	Swede Peak, ID	13F09S	7640	43°37'	113°58'
I	Bear Canyon, ID	13F03S	7900	43°45'	113°56'

The linear regression equation which can be developed from an historical relationship between a specific target and a control is of the form:

$$Y_C=A+B(X_O) \quad (1)$$

where Y_C is the average calculated snow water content, in the target area, A is a constant (the intercept of the regression line with the Y-axis); B is also a constant (the slope of the regression line) and X_O is the average observed amount of the snow water content in the control area.

When the April 1 snow water content at the original control sites was averaged for the historical not seeded water years of 1961-1992 and 1998-2001 and compared to the average for the target area snow water content, the two groups provided were found to be strongly correlated with one another with a correlation coefficient (r) of .976. This means that approximately 95% of the variance (r^2) is accounted for in the regression equation developed from the historical (non-seeded) period. The average elevation of the control sites is 6,377 feet MSL compared to a target area average of 7,387 feet MSL.

The specific equation developed from the historical relationship between the seven original control sites and the nine target sites is as follows:

$$Y_C = -0.96 + 1.22 (X_O) \quad (2)$$

The seeding effect (SE) can be expressed as the ratio (R) of the average observed target snow water content to the average calculated snow water content, such that:

$$SE = R = Y_O / Y_C \quad (3)$$

where Y_O is the average target area observed snow water content (inches) and Y_C is the average target area calculated snow water content.

The seeding effect can also be expressed as a percent excess (or deficit) of the expected snow water content in this form:

$$SE^* = \{\{Y_O - Y_C\} / Y_C\} * (100) \quad (4)$$

where $SE^* = SE\ (100)$

5.2.3.3 Regression Equation Development for Alternate Control Group

April 1 snow water content measurements were totaled at each site location in the alternate control and target areas in each of the historical water years from 1961-1992 and 1998-2001 (36 water years) and seasonal averages for each group were obtained. The predictor equation was developed from these data via a linear regression analysis.

The specific equation developed from the historical relationship between the nine (alternate) control sites and the nine target sites is as follows:

$$Y_C = -2.86 + 1.25\ (X_O)$$

5.2.3.4 Snowpack Evaluation Results

The observed average value of the April 1, 2009 snow water content at the nine alternate control sites was 20.6 inches. When this number was entered as the X_O value in equation (2) the calculated (most probable) value of the target area snow water content was $Y_C = 22.8$ inches. The actual average observed snow water content for the target area sites was 21.6 inches, or 1.2 inches less than predicted. From equation (3) the ratio of the observed target average snow water content to the calculated target average snow water content was 0.95, indicating that the target area reported approximately 5% less snow water content than would have been predicted based on the this alternate control site average for this particular season. Table 5-5 shows multi-season results through 2009 using the alternate control set.

Single-season results should always be viewed with caution due to the statistical limitations of the evaluation method. Combined results from all seeded seasons (a total of 10 for the Boise River program) are considered to be much more significant than results from an individual season. This is because seasonal variations in weather and temperature patterns lead to variable individual season results.

Table 5-5 Snowpack Evaluation Results (alternate control sites)

Water Year	Control Avg.	Target Avg.	Target	Obs/Pred	Excess
Regression Equation: $Y_C = -2.86 + 1.25 (X_O)$					
1993	22.51	27.09	25.24	1.07	1.85
1994	13.59	13.76	14.10	0.98	-0.35
1995	23.83	30.91	26.89	1.15	4.02
1996	22.74	28.13	25.53	1.10	2.61
2002	22.86	22.10	25.67	0.86	-3.57
2003	18.57	22.37	20.31	1.10	2.05
2004	19.42	19.52	21.38	0.91	-1.86
2005	14.70	15.88	15.49	1.03	0.39
2008	24.33	25.73	27.51	0.94	-1.78
2009	20.58	21.62	22.82	0.95	-1.20
Average*	**20.31**	**22.71**	**22.49**	**1.01**	**0.22**

*The average ratio is calculated from the average target values (observed and predicted) for all nine seeded seasons, and is thus a weighted mean; it is not obtained by averaging individual year ratios

Similar calculations were made to those reported above utilizing the original control sites as documented in Table 5-6. The linear regression equation used was $Y_C = - 0.96 + 1.22(X_O)$. When the average of the control sites, 19.09, was inserted into this equation, the calculated target average was 22.32 inches of snow water content. The actual snow water content was 21.62 inches indicating a difference of –0.70 inches and a ratio of 0.97. Table 5-6 shows the multi-season results through 2009 for the original control set.

Table 5-6 Snowpack Evaluation Results (original control sites)

Water Year	Control Avg. (inches)	Target Avg. (inches)	Target Predicted	Obs/Pred Ratio	Excess (inches)
Regression Equation: $Y_C = -0.96 + 1.22 X_O$					
1993	20.29	27.09	23.79	1.14	3.30
1994	11.63	13.76	13.23	1.04	0.53
1995	21.84	30.91	25.69	1.20	5.22
1996	22.89	28.13	26.96	1.04	1.17

Water Year	Control Avg. (inches)	Target Avg. (inches)	Target Predicted	Obs/Pred Ratio	Excess (inches)
2002	20.69	22.10	24.28	0.91	-2.18
2003	19.00	22.37	22.22	1.01	0.15
2004	16.69	19.52	19.40	1.01	0.13
2005	12.91	15.88	14.80	1.07	1.08
2008	24.20	25.73	28.56	0.90	-2.83
2009	19.09	21.62	22.12	0.97	-0.70
Average*	**18.92**	**22.71**	**22.12**	**1.03**	**0.59**

*The average ratio is calculated from the average target values (observed and predicted) for all nine seasons, and is thus a weighted mean; it is not obtained by averaging individual year ratios; some data may differ slightly from that previously reported, due to the replacement of preliminary data (at some sites) with official data.

Complete historical and seeded season snow water content information is provided in Appendix C.

The results for all ten seeded seasons using two different control areas are somewhat similar to each other in terms of indicated average increases of +1-3%. The average differences range from 0.22 to 0.59 inches of additional snow water content. The negative ratios in a handful of seasons should not be interpreted as indicating that cloud seeding decreased the snowpack during those seasons, since we are not aware of any means by which cloud seeding could reduce seasonal precipitation in the target area. Rather, the reductions in snowfall suggested for some seeded seasons are believed to be due to seasonal variations in precipitation patterns, which cannot be accounted for using the linear regression technique or the available historical data. Since the mathematical errors in estimation theoretically affect both tails (i.e. can be positive or negative), those errors tend to cancel one another in the long-term average. Thus, the multi-season average values are probably more realistic estimates of the overall seeding effects.

5.2.4 Evaluation of Precipitation in the Target Area

Precipitation data used in the analyses were obtained from the Natural Resources Conservation Service (NRCS) and/or from the National Climatic Data Center, and represent the official published records of those organizations. When the NRCS, known then as the Soil Conservation Service (SCS), introduced the SNOTEL data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before this system was developed, data had to be acquired by visiting the site to make manual measurements (e.g. snow surveys), which is still being done to the present time at a few sites in the western United States.

Historic high elevation precipitation data in Idaho are not readily obtainable prior to the implementation of the SNOTEL program in the early 1980's. NAWC, in early evaluations of the Boise program, had used in-house estimates of high elevation precipitation. We utilized these data in combination with SNOTEL data to perform one of our precipitation evaluations (one we identify as the original control site analyses). We only used SNOTEL data in the other precipitation analyses that we identify as the alternate control analyses sine we did not have the longer term data available to us for these new sites. The data that are available from the SNOTEL sites cover a much shorter period of record and therefore this second analysis may not be as robust as the first analysis (snowpack) based upon a longer historical period.

5.2.4.1 Target Area Gage Sites

Precipitation measurements were used from eleven sites within and immediately downwind of the target area. These were the same sites as those used previously dating back to 1996, with the addition of Idaho City. The Idaho City site, an NWS cooperative reporting station, improves coverage over the target area by representing the western side of the seeding target area. Except for Idaho City and Prairie, all the rest of the target sites are SNOTEL sites. These sites are listed in Table 5-7 and their locations are shown in Figure 5.10, with labels corresponding to those shown in the table. The average elevation for the target area sites is 6,805 feet MSL.

Table 5-7
Precipitation Target Sites

Map ID	Site Name	NRCS ID	Elev. (Ft)	Lat. (N)	Long (W)
1	Atlanta Summit	15F04S	7580	43° 45'	115° 14'
2	Dollarhide Summit	14F08S	8420	43° 36'	114° 40'
3	Galena Summit	14F12S	8780	43° 51'	114° 43'
4	Graham Guard Stn.	15F14S	5690	43° 57'	115° 16'
5	Jackson Peak	15E09S	7070	44° 03'	115° 27'
6	Mores Creek Summit	15F01S	6100	43° 55'	115° 40'
7	Prairie	ID7327	4780	43° 30'	115° 35'
8	Soldier R.S.	14F11S	5740	43° 29'	114° 49'
9	Trinity Mountain	15F05S	7770	43° 38'	115° 26'
10	Vienna Mine	14F04S	8960	43° 48'	114° 51'
11	Idaho City	ID4442	3970	43°50'	115°50'

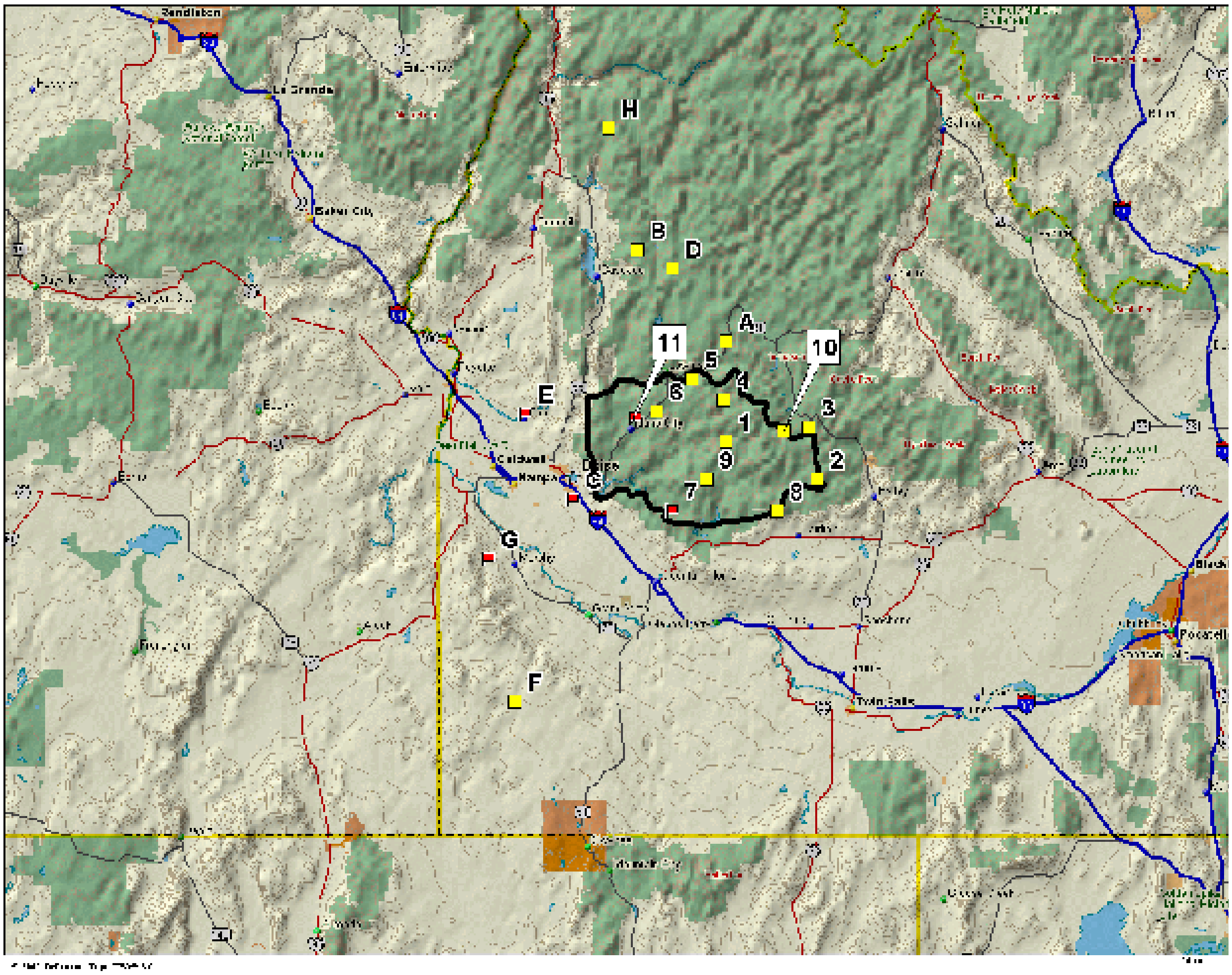

Figure 5.10 Target Sites (numbers) and Original Control Sites (letters) used in earlier Precipitation Evaluations. (Squares represent SNOTEL sites, and flags are NWS cooperative stations; labels correspond to Tables 5-7 and 5-8)

5.2.4.2 Control Area Gage Sites

The same issue was encountered when conducting the precipitation analysis as with snow water content: the seeding the previous four winters in the Payette drainage may have contaminated some of the control sites used in previous evaluations. Three of the eight control sites are located within or near the Payette drainage. As a consequence, results will be presented for both the original and an alternate set of control sites, as was done with the snowpack analysis.

5.2.4.3 Regression Equation Development

The original set of control sites is the same as that utilized in earlier evaluations. It is also the same as the 1996 set, with the exception of Council, which was dropped last year due to poor data quality. Six of the control group sites extend along an approximate north to south line from Secesh Summit (105 miles north of Boise) to Mud Flat (70 miles south of Boise) with the other two control sites located in the mountains 25-50 miles north of the northern boundary of the Boise River drainage. In this regard, winter storms affecting the target area will also affect the majority, if not all, of the control group gages as well. The average elevation of the original control area gage sites is 5,236 feet MSL. The site locations are plotted in Figure 5.10, with labels corresponding to those listed in Tables 5-7 and 5-9.

For the original set of control sites, precipitation values were totaled at each gage in the control and target area for the December-March period (this period represents the whole months that have typically been seeded) in each of the historical water years from 1968-1992 and 1998-2001 (29 seasons), and averages for each group were obtained. The 1997 water year was excluded from this historical data set since there was seeding conducted in the Payette River drainage during the 1996-97 winter season. This data set contained some estimates of monthly precipitation prior to the implementation of the NRCS SNOTEL program that began in the early 1980's. The predictor equation was developed from these data for the four-month period. This equation was $y = 1.25(x) - 1.68$. This control group provides a very strong correlation of $r = .989$ with the target, yielding a variance (r^2) of .978.

Table 5-8
Original Precipitation Control Sites (see Fig. 5.10)

Map ID	Site Name	NRCS ID	Elev. (Ft)	Lat. (N)	Long (W)
A	Banner Summit	15E11S	7040	44° 13'	115° 14'
B	Big Creek Summit	15E02S	6580	44° 38'	115° 48'
C	Boise WSFO AP	ID1022	2838	43° 34'	116° 13'
D	Deadwood Summit	15E04S	6860	44° 33'	115° 34'
E	Emmet 2E	ID2942	2390	43° 52'	116° 28'
F	Mud Flat	16G07S	5730	42° 36'	116° 33'
G	Reynolds	ID7648	3930	43° 12'	116° 45'
H	Secesh Summit	15D01S	6520	45° 11'	115° 58'

A grouping of eight sites was judged to be the best alternate control group (this control group was examined to avoid the question of contamination of some of the original control sites due to seeding in the Payette River drainage) in the evaluation prepared for the 2002-03 winter season, based upon: 1) their correlation with the target area, 2) geographic bracketing of the target area, and 3) similarity to the target area in terms of elevation and meteorology. The historical years of 1982-1992, and 1998-2001, were used in the development of the linear regression equation. This period was used, as stated earlier, to include only the period that data were available from SNOTEL observations (i.e. no estimated data), and excluded the water year of 1997, which was a seeded year in the Payette drainage. Figure 5.11 provides the locations of these alternate sites and Table 5-9 provides the names of the sites.

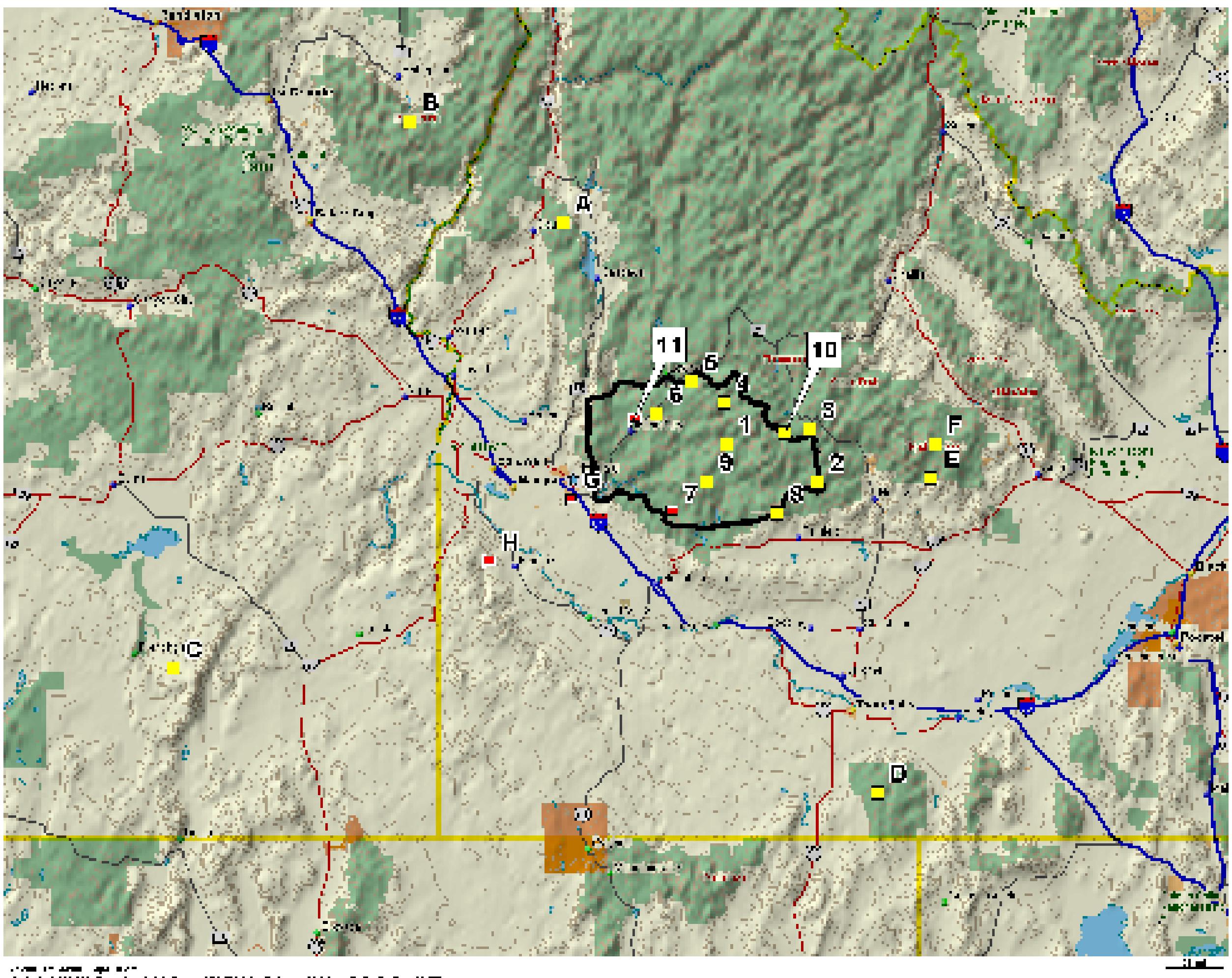

Figure 5.11 Target and Alternate Control Sites used in Precipitation Evaluations. (Squares represent SNOTEL sites, and flags are NWS cooperative stations; labels correspond to Tables 5-7 and 5-9)

Table 5-9
Alternate Precipitation Control Sites (see Fig. 5.11)

Map ID	Site Name	NRCS ID	Elev. (Ft)	Lat. (N)	Long (W)
A	Squaw Flat, ID	16E05S	6240	44°46'	116°15'
B	Aneroid Lake #2, OR	17D02S	7300	45°13'	117°12'
C	Silvies, OR	18G01S	6900	42°45'	118°41'
D	Magic Mountain, ID	14G02S	6880	42°11'	114°18'
E	Swede Peak, ID	13F09S	7640	43°37'	113°58'
F	Bear Canyon, ID	13F03S	7900	43°45'	113°56'
G	Boise WSFO AP	ID1022	2838	43° 34'	116° 13'
H	Reynolds	ID7648	3930	43° 12'	116° 45'

The linear regression equation developed from the historical relationship between the alternate control versus the target group is as follows:

$$Y_C=0.46+1.31X_O$$

Where:
Y_C is the calculated average target precipitation (inches) and X_O is the eight-station control average observed precipitation (inches) for the December – March period.

This equation has a relatively high r value of 0.94 and an r^2 value of 0.89.

5.2.4.4 Precipitation Evaluation Results

When the observed average **alternate** control precipitation (14.11 inches) for the December, 2008 through March, 2009 period was inserted into the regression equation, the most probable average target area precipitation using the alternate control site grouping was calculated to be 18.98 inches. The actual observed average precipitation for the ten gages in the target group was 19.71 inches. This is an average of 0.7 inches more precipitation observed in the target area than predicted. From the regression equation, the 2009 season ratio of target area observed to calculated precipitation is 1.04, or 4% more than predicted by the regression equation. The combined eight-season observed/predicted ratio is 1.07, which corresponds to an average excess of 1.4 inches of water in the target area.

Table 5-10 provides results obtained with the alternate control group selected for this current season's evaluation as well as for multiple seeded seasons. Table 5-11 summarizes the indicated results using the original control sites.

Complete historical and seeded season precipitation information is provided in Appendix C.

As indicated in the discussion of the snow water content results for this past season, the prevailing pattern last winter favored the control gage sites over the target sites in terms of precipitation accumulation. As a result the predicted target precipitation is probably on the high side, which may obscure the effects of seeding.

Table 5-10
Precipitation Evaluation Results (alternate control sites)

Water Year	Control Avg. (inches)	Target Avg. (inches)	Target Predicted	Obs/Pred Ratio	Excess (inches)
Regression Equation: $Y_C = 0.46+1.31X_O$					
1993	14.83	22.17	19.92	1.11	2.25
1994	8.59	13.41	11.72	1.14	1.69
1995	15.29	24.34	20.52	1.19	3.82
1996	16.72	25.34	22.40	1.13	2.94
2002	13.83	18.15	18.61	0.98	-0.46
2003	14.03	21.26	18.87	1.13	2.39
2004	14.12	18.44	18.99	0.97	-0.55
2005	10.00	13.28	13.58	0.98	-0.29
2008	15.28	21.57*	20.51	1.05*	1.06*
2009	14.11	19.71	18.98	1.04	0.73
Average*	**13.67**	**19.77**	**18.40**	**1.07****	**1.37**

*The average ratio is calculated from the average target values (observed and predicted) for all eight seasons, and is thus a weighted mean; it is not obtained by averaging individual year ratios.

Table 5-11
Precipitation Evaluation Results (original control sites)

Water Year	Control Avg.	Target Avg.	Target	Obs/Pred	Excess
Regression Equation: $Y_C=-1.68+1.25X_O$					
1993	18.62	22.17	21.58	1.03	0.58
1994	10.83	13.41	11.86	1.13	1.55
1995	19.47	24.34	22.65	1.07	1.69
1996	21.85	25.34	25.62	0.99	-0.28
2002	15.02	18.15	17.08	1.06	1.06
2003	19.69	21.26	22.92	0.93	-1.65
2004	15.06	18.44	17.14	1.08	1.30
2005	10.44	13.28	11.36	1.17	1.92
2008	16.70	21.57	19.19	1.12	2.38
2009	15.00	19.71	17.07	1.15	2.65
Average*	**16.27**	**19.77**	**18.65**	**1.06****	**1.12**

*The average ratio is calculated from the average target values (observed and predicted) for all eight seasons, and is thus a weighted mean; it is not obtained by averaging individual year ratios; some data may differ slightly from that previously reported, due to the replacement of preliminary data (at some sites) with official data.

The results for all ten seeded seasons using two different control areas are supportive of each other in terms of indicated average differences of 6% to 7% increases in December through March precipitation in the target area. The average difference ranges from 1.12 to 1.37 inches of additional December through March precipitation. It is important to remember, as discussed in the snowpack results section, that negative ratios in some seasons should not be interpreted as indicating that cloud seeding decreased the precipitation during those seasons, since we are not aware of any means by which cloud seeding could reduce seasonal precipitation in the target area. Rather, the reductions in precipitation indicated for some seeded seasons are probably due to imprecise indications of the natural precipitation in the target area from the linear regression estimation technique. The multi-season average values should provide more reasonable estimates of the overall seeding effects.

5.2.5 Discussion of Evaluations

Alternate control site groupings were developed for both the snowpack and precipitation evaluations, in an attempt to reduce the potential contamination problem that might result from seeding in the Payette Drainage, immediately north of the Boise River seeding program. In the development of these control site groupings, the main goals were to obtain: 1) a high degree of correlation with the target area, 2) geographic bracketing of the target area, and 3) similarity (in terms of elevation and meteorology) to the target. The target area sites are the same as those used previously. Results pertaining to both (original and revised) control site groupings are provided for both snowpack and precipitation types of observations. As pointed out in the preceding, each type of observation may be subject to different types of measurement errors.

Evaluation of this year's April 1st snow water equivalent data and December - March precipitation data, using alternate control sites, yielded observed/predicted target area ratios of 0.95 and 1.04, respectively. These ratios would suggest a 5% decrease or 4% increase, respectively. Again it is important to point out that single-season ratios have little significance, and the decreases are attributed to variations in natural precipitation patterns between the target and control areas, which can outweigh positive seeding effects during a given season. A seeding program conducted this past season, immediately to the north of the Boise River program, most likely affected some of the original control sites. The original control set yielded ratios of 0.97 and 1.15 for this season in the snowpack and precipitation evaluations, suggesting a 3% decrease or 15% increase, respectively.

Longer-term (multiple seeded season) averages of the evaluation results provide a much more reliable indication of the effects of the cloud seeding. **Results using the original target and control groups for the nine seeded seasons suggest average precipitation and snowpack increases of approximately 6% and 3%, respectively. The independently developed alternate control site group for the ten seeded seasons suggest average precipitation and snowpack increases of approximately 7% and 1%, respectively.**

5.2.6 Estimates of Increases in Streamflow

An estimate in streamflow increase due to cloud seeding was published in Griffith and Solak (2002), where a 12% increase in April 1st snow water content due to cloud seeding was used. As a follow-up to this, the same streamflow equation is used here, with an estimated 4% increase in snow water content due to cloud seeding. The equation is $y = 33.2x + 167.5$, where y is the annual average runoff at Twin Springs (in cfs) and x is the Atlanta Summit April 1 snow water content (in inches). From the 2002 study, the annual average runoff at Twin Springs for the 20-year base period (unseeded) was 1252 cfs. The corresponding average snow water content at Atlanta Summit was 32.7". When the snow water content value was increased by 12% to 36.6", the resultant average streamflow at Twin Springs was 1369 cfs, an increase of 9.4%. When the Atlanta Summit snow water content is increased by 4%, to 34.0", the resultant average streamflow at Twin Springs is 1296 cfs, an increase of 3.5% from the 1252 cfs base period average. Using the same four seeded years examined in the study, with an average annual runoff at Twin Springs of 1321 cfs (956,404 acre feet), the result of a 3.5% streamflow increase is an additional 33,474 acre feet annually at the Twin Springs location.

The study then continued by examining the average 10-year (1991-2000) discharge from Lucky Peak Dam, which led to an estimated annual runoff of 1,096,621 acre feet in the South Fork Drainage. A 3.5% increase in this value equals 38,382 acre-feet. **Add to this the number the estimated 33,474 acre feet increase at the Twin Springs site, results in a total estimated annual increase of 71,856 acre feet of runoff resulting from a 4% increase in snow water content due to cloud seeding. With an average cloud seeding budget of $90,000 during this period, the average cost would be $1.25 per acre-foot. Further, if half of this additional runoff could be used for power production (as assumed in the original study, which is considered to be a very conservative estimate), this is equivalent to 35,928 additional acre-feet of water for power production. Using the average 0.17 mwh of electricity estimated to be produced per acre-foot, and an estimated $50 value per mwh, this results in an estimated increase in power production valued at $305,388 per water year, due to a 4% increase in snowpack. The estimated benefit/cost ratio, strictly from power production, is 3.4/1. This ratio would be higher if the value of the additional streamflow to agriculture was included.**

6.0 EVALUATE ENHANCEMENTS TO EXISTING PROGRAM (Task 3)

6.1 Options to Enhance Exiting Program

There are basically three options that could be considered to enhance the results being achieved in the current upper Boise River operational program: 1) extend the current operational program to six months (November through April) instead of five months, 2) adding remote generators to the program, and 3) adding airborne seeding capabilities to the program. Improvement in the results, by adopting the second or third options, is addressed in the following section.

6.2 Estimates of Precipitation and Streamflow Increases

As required in the contract, NAWC was tasked to produce an estimate of the additional water that could be provided by the snowpack augmentation program, provided in terms of acre-feet of runoff. There are two steps that need to be accomplished in providing these estimates. The first step is to estimate the impact of cloud seeding on precipitation in the target area. The second step is to convert these estimated increases in precipitation into estimates of increases in streamflow. The approach used to accomplish the first step is discussed in next section. The approach used to accomplish the second step is discussed in the following section.

6.2.1 Estimates of Precipitation Increases

Developing quantitative estimates of the effects of seeding presents a challenge, but is a necessary step in order to develop reasonable estimates of increases in streamflow. The technique used to develop the quantitative estimates of increases in precipitation is discussed in the following.

As discussed previously, a detailed analysis of storm periods affecting the target area was conducted for an 8-season period (water years 2001-2008) for the October-April season. Precipitation data from several SNOTEL sites were considered, and six-hour time blocks were selected when precipitation was clearly occurring in the target area, as discussed earlier in this section. Data were examined from three SNOTEL sites in the Boise River Basin. The SNOTEL data ranged from hourly to six-hourly in resolution and were obtained from the Natural Resources Conservation Service (NRCS).

A total of 386, 6-hour periods were selected for analysis, generally corresponding to precipitation at the SNOTEL sites averaging more than about 0.1" and generally with precipitation evident at least three of the sites. These six-hour periods were matched as closely as possible to Boise weather balloon soundings, which we believe to be a good representation of this area. These soundings were used to derive temperature and wind data at the 700-mb and 500mb levels, which are at approximately 10,000 and 18,000 feet MSL. The soundings also provided moisture (dewpoint) values, a general idea of low to mid-level atmospheric stability. Estimates of the $–5^0$ C isotherm height and cloud-top temperature were obtained based on these sounding profiles as well.

As previously discussed, low-level stability (which could prevent seeding material from reaching the $–5^0$ C level over the target area) was classified into four categories: Well-mixed or neutral conditions (no stability problems evident which should mean that silver iodide particles released near the surface can be transported over the mountain barriers in the storm winds), slightly stable, moderately stable, and very stable. These categories correspond roughly to situations when less than 2^0 C of surface heating would be necessary to mix out the atmosphere (slightly stable), 2-4^0 C (moderately stable), and more than 4^0 C (very stable). Cases that were well mixed or slightly stable were considered suitable for lower elevation ground-based seeding, while more stable cases would require remote high-elevation or aircraft seeding.

We used the results from a well-known, randomized research weather modification program conducted in the Climax region of the central Colorado Rocky Mountains in two phases, Climax I (1960-65) and Climax II (1965-70) (Mielke, et al, 1981) to estimate the potential seeding effects in the UBRB program. These experiments utilized ground-based releases of silver iodide in 24-hour treatment periods. The detailed statistical analyses indicated that precipitation was increased by 25%-41% (depending upon whether a single or double ratio analysis was used) when 500mb (approximately 18,000 feet) temperatures were in the $–4^0$ to $+12.2^0$ F (-20^0 C to $–11^0$ C). These results were statistically significant at the .05 level. Other reports on the two Climax programs indicated positive effects of seeding at 500mb temperature ranges of ~ -5.8^0 to $–14.8^0$ F (-21^0 to $– 26^0$ C). One report (Hess, 1974) indicated approximately 10% increases in this 500mb temperature range. NAWC used this information to derive an estimate of the possible seeding increases in the UBRB as discussed in the following.

In our earlier work in the Eastern Snake River Basin (Griffith, et al, 2008), we produced cloud top temperature estimates based on weather balloon sounding data instead of utilizing the 500-mb temperature, which we believe to be a more direct approach to the physics of the situation. We performed an analysis of the percentage of the six-hour events that had cloud top temperatures in a "seedable" range of $–5^0$ to $–25^0$ C based upon the Climax I and II results. The lower limit of $–25^0$ C is similar to indications of seedable conditions in northern Utah (Hill, 1980 b) and northern Colorado (Rauber and Grant, 1986), both of which determined conditions to be seedable when the 500-mb temperature was $–22^0$ C or warmer. Of the 386 6-hour periods examined, 109 periods (or 28%) were considered seedable based on having a cloud-top temperature between -5 and -25^0 C (Figure 6.1).

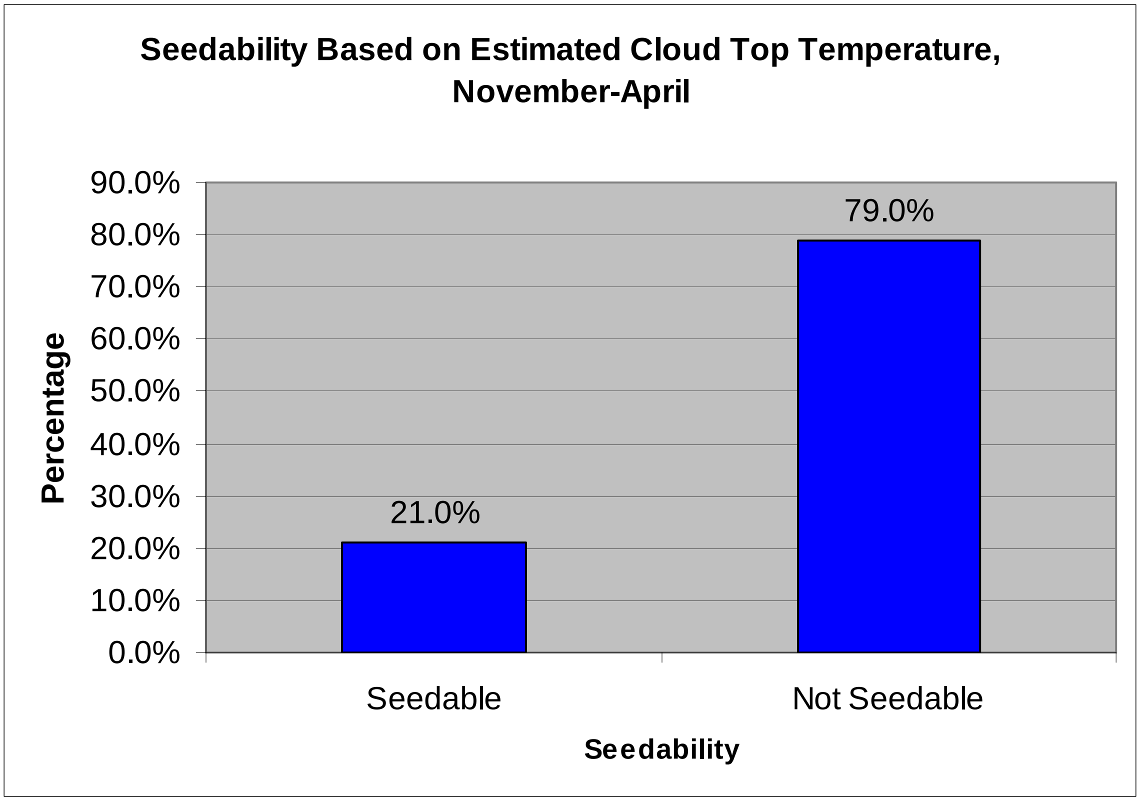

Figure 6.1 Storm Periods Considered Seedable Based upon Estimated Cloud Top Temperatures

The basic seeding potential during six-hour periods that occurred from November through April was calculated using results from Climax I and II studies in Colorado (except that cloud-top temperature was utilized instead of 500-mb temperature as was done for the Eastern Snake River Basin study). The month of October was excluded due to limited snowpack accumulation during this month and relatively warm temperatures at the 700 mb level. The seeding potential was considered to be +25% when cloud-top temperature was between -5^0 C and -20^0 C, +10% for cloud-top temperatures of -21^0 to -25^0 C, and 0% for cloud-top temperatures of -26^0 C or colder (or warmer than -5^0 C). This seeding potential was then sub-divided between different seeding modes or methods, including manual ground-based, remote ground-based, and aircraft seeding. The seeding potential for a given 6-hour time period was assigned to ground-based seeding if a) the low-level air mass was classified as well-mixed or only slightly stable, and b) The 700-mb temperature was -5^0 C or colder. Similarly, the seeding potential was assigned to remote, high-elevation seeding sites if low-level stability was classified as "moderate" or higher and the 700-mb temperature was -5^0 C or colder. Seeding potential was assigned to aircraft-only for cases where the 700-mb temperature was above -5^0 C regardless of stability considerations. These divisions are summarized in the following:

The assumptions made to accomplish this stratification were:

For lower elevation manually operated silver iodide generators

1. The low level atmospheric stability (surface to the 700 mb level) was neutral or slightly stable.
2. The 700 mb temperature was ≤ -5^0 C, 23^0 F.

For higher elevation remotely operated silver iodide generators

1. The low level atmospheric stability was moderately or very stable
2. The 700 mb temperature was ≤ -5^0 C, 23^0 F.

For Aircraft silver iodide seeding

1. The 700 mb temperature was > -5^0 C, 23^0 F.

It should be noted that the use of remote generators assume these generators could be placed at locations above the inversions that would prelude the use of manually operated generators that are typically located at lower elevations. Higher elevation remote generators might be used in conditions classified as seedable using lower elevation, manually operated generators, although some of the concerns like those depicted in Figure 3.12 would still apply. We, however, decided to start with the least expensive (or most economical), yet effective technology first in our determination of seeding potential using various modes. This is the reason for the cumulative progression in seeding potential from manually operated ground-based generators, to remotely controlled ground -based generators, and finally to aircraft. Aircraft seeding could be used under most conditions (except in a few circumstances such as very shallow clouds); however, our focus for any potential aircraft seeding is in situations that probably could not be effectively seeded using ground generators of either type.

The potential seeding increases from the Climax program (10% or 25%) were applied to the average of the three SNOTEL sites. These calculated increases were then summed, along with the average amounts of precipitation for the three sites, for the eight-season period. An average percentage increase was then calculated based upon these eight seasons of data. This percentage was then applied to the long-term average seasonal precipitation (e.g., November-March, November-April) at five SNOTEL sites (two SNOTEL sites were added, Camas Creek Divide and Trinity Mountain, to this analyses to provide more representative information for the target area). The result was an estimate of the potential average increase in precipitation expressed in inches of water. The average percentage increases and the average amounts of these increases were also calculated according to the three seeding modes. This approach makes at least three assumptions as follows:

1. The six-hour precipitation data represent essentially all of the precipitation that occurred during the eight winter seasons at the three sites. This is probably a reasonable assumption since we tracked events that had at least 0.10 inches of water at two out of the three sites. There may be minor

amounts not accounted for when 0.10 inches occurred at only one of the three sites.

2. The eight season data set covers a long enough period to be considered climatologically representative. For example, if all eight-winter seasons happened to be below normal then these results would under estimate the seeding potential.
3. The estimated increases calculated for the 6-hour periods can be extrapolated to estimate total seasonal increases in the April 1st water content.

Figure 6.2 provides the estimated percentage of the "seedable" cases that would potentially be seedable (based on cloud top temperatures, lower-level atmospheric stability and 700mb temperatures criteria discussed in the above) using the three different seeding modes (manual ground generators, remotely controlled ground generators and aircraft).

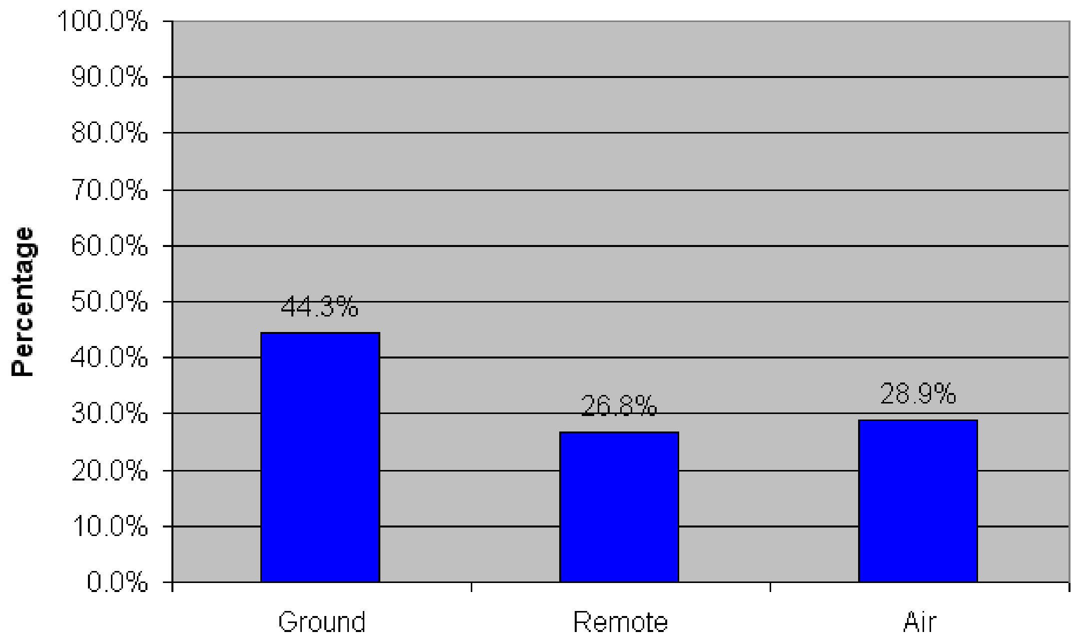

Figure 6.2 Distribution of Seedable 6-hour Periods According to Most Economical Seeding Mode, November - April Period

This figure shows that about 44% of the seedable periods during November - April were considered seedable by ground-based generators; an additional 27% were considered seedable by remote high-elevation generators, and the remainder (29%) were considered to be only seedable by aircraft. The estimated increases for the November – March and November-April periods are provided in Figures 6.3 and 6.4. These figures show an estimated 1.7% precipitation increase due to manual ground-based seeding only; an additional 1.5-1.6% increase possible with high-elevation remote generators; and a further 1.5-1.9% increase with the use of aircraft. This is a total estimated increase of 4.7-5.1% for all seeding modes.

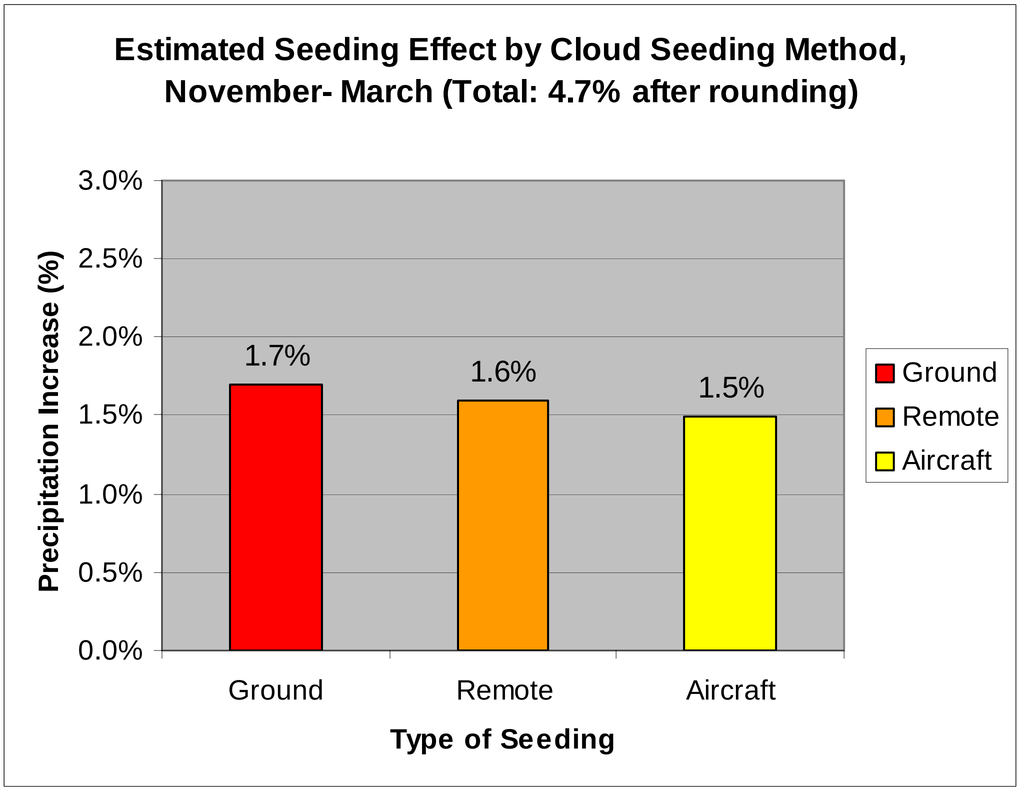

Figure 6.3 **Estimates of Percentage Increases in November – March Precipitation for Seedable Cases Partitioned by Seeding Mode**

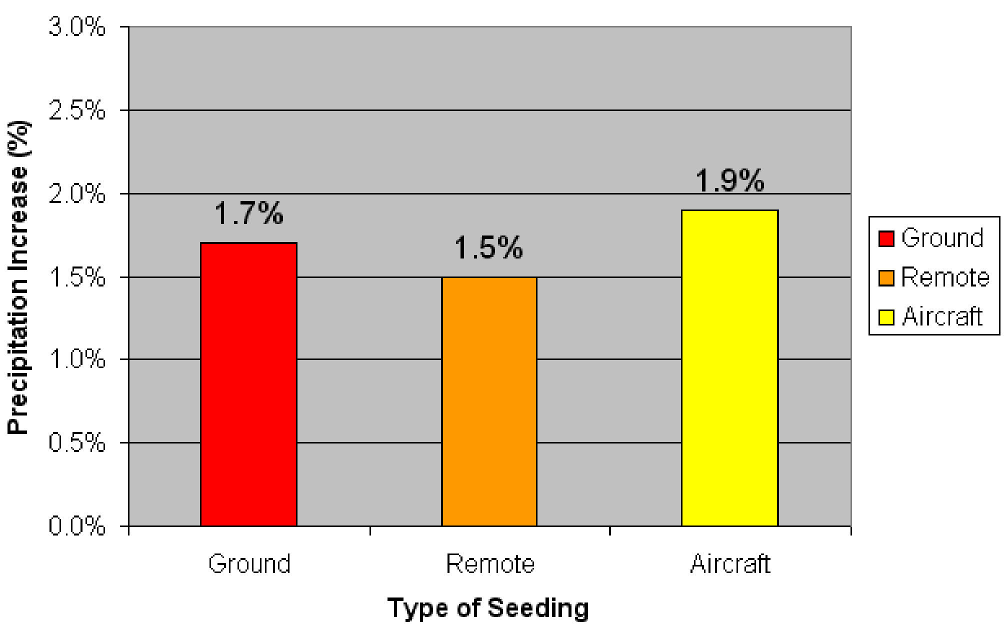

Figure 6.4 **Estimates of Percentage Increases in November – April Precipitation for Seedable Cases Partitioned by Seeding Mode**

Tables 6-1 and 6-2 provide the estimated average percentage increases and amounts of the increases expressed in inches for the November-March and November-April periods.

Table 6-1 Estimates of Increases in Average November-April Precipitation by Seeding Mode

Site	Nov-Apr Precip	Total Increase (5.1%)	Ground (1.7%)	Remote (1.5%)	Air (1.9%)
Atlanta Summit	33.3	1.70	0.57	0.50	0.63
Soldier R.S.	15.3	0.78	0.26	0.23	0.29
Mores Creek Sum	35.0	1.79	0.60	0.53	0.67
Camas Creek Div	15.0	0.77	0.26	0.23	0.29
Trinity Mtn	41.0	2.09	0.70	0.62	0.78
Average	**27.92**	**1.42**	**0.47**	**0.42**	**0.53**

Table 6-2 Estimates of Average Increases in April 1st Snow Water Content by Seeding Mode (Based on November-March storm periods)

Site	Apr 1 SWE	Total Increase (4.7%)	Ground (1.7%)	Remote (1.6%)	Air (1.5%)
Atlanta Summit	31.9	1.50	0.54	0.51	0.48
Soldier R.S.*	10.0	0.47	0.17	0.16	0.15
Mores Creek Sum	34.6	1.63	0.59	0.55	0.52
Camas Creek Div*	8.2	0.39	0.14	0.13	0.12
Trinity Mtn	39.5	1.86	0.67	0.63	0.59
Average	**24.84**	**1.17**	**0.42**	**0.40**	**0.37**

In summary, the estimated possible increase in average November through April precipitation using ground-based manual generators is 0.47"; an additional 0.42" is estimated with the use of remote high-elevation generators, and a further 0.53" is possible using aircraft. The combination of all three seeding modes is predicted to result in an average increase in November through April precipitation of 1.42".

The resulting estimated increases in average April 1st snow water content are 0.42" using ground-based manual generators; an additional 0.40" using high-elevation remote generators, and a further 0.37" is possible using aircraft. The total estimated April 1st snow water content increase is 1.17" using all three seeding modes.

The importance of seeding during the month of April is shown in the difference in the numbers when comparing Table 6-1 (based on November-April events) and Table 6-2 (based on November-March events). The winter snowpack typically begins to melt around April 1st. Cloud seeding will continue to increase the snow water content after this but these increases in April will be masked due to the snowmelt. Therefore, the

November through April precipitation increases are probably more representative of the potential increases in precipitation that can then be converted into estimates of increases in streamflow.

The range of potential seeding increases in precipitation is supported by a World Meteorological Statement on cloud seeding capabilities. The Policy Statement of the World Meteorological Organization (WMO) on winter orographic clouds states (WMO, 1992):

> *In our present state of knowledge, it is considered that the glaciogenic seeding of clouds or cloud systems either formed, or stimulated in development, by air flowing over mountains offers the best prospects for increasing precipitation in an economically viable manner. These types of clouds attract great interest in modifying them because of their potential in terms of water management, i.e., the possibility of storing water in reservoirs or in the snowpack of higher elevation. Numerous research and operational programs conducted since the beginning of weather modification as a science provide the evidence. Statistical analyses suggest seasonal increases (usually over the winter/spring period) on the order of 10 to 15% in certain program areas.*

Other capability statements from the Weather Modification Association and the American Meteorological Association provide estimates of seeding increases in a similar range (e.g., 10-15%) in winter orographic conditions.

6.2.2 Comparison of Estimated Results from Existing Program versus the Estimated Theoretical Potential

The theoretical estimates of increases in precipitation found in section 6.2.1 can be compared to the indicated increases in precipitation through the conduct of the operational program as contained in section 5.2.4.3. The theoretical estimate for manually operated ground generators is 1.7% for the November through March period. The average results from NAWC's operational program is in the 6-7% range for the December through March period. This difference could be due to at least two basic considerations: 1) NAWC's theoretical estimation procedure makes some assumptions rendering conservative estimates of increases or 2) NAWC's evaluation of the operational program is too optimistic for unforeseen reasons. In regards to item #1, our theoretical estimates might be too low since we assume no potential increases if the cloud top temperatures are $< -25^0$ C. Recall that 80% of the precipitation periods from our eight-season analysis were considered not seedable based upon this criterion. Even a 1-2% increase in these cold cloud top cases would significantly raise our theoretical estimates. In the case of #2, it may be that our estimates for increases in precipitation are too high due to the relatively few seeded seasons (10 seasons) or inaccuracies in the historical regression analysis technique. It is interesting to consider the estimates of increases in April 1st snow water contents from the operational program. These estimates range from 1-3% which are in much better agreement with the theoretical estimates. It is difficult to ascertain the relative accuracy of the two approaches. **Since NAWC used the theoretical estimates of increases in precipitation to estimate the increases in streamflow in the following section, we conclude that these streamflow estimates may be somewhat on the conservative side.**

6.2.3 Estimated Increases in Streamflow

The Idaho Water Resource Board (IDWR) provided NAWC with monthly historical streamflow data for the Boise River at several USGS sites. Three of these sites had data during the 1982-2008 period for which regressions could be developed with available SNOTEL precipitation and snowpack data. After comparison with the SNOTEL data, two of these streamflow gage sites were selected based on their good correlations with the precipitation/snowpack data, as well as their location (one on the South Fork and one on the Middle Fork of the Boise River). Information on these sites is as follows:

- USGS #13185000 (Middle Fork)
- USGS #13186000 (South Fork)

These two sites are considered unregulated and the March-July streamflow totals had good correlations (r values ~0.92-0.94) with both the November - April precipitation and the April 1 snow water content at four SNOTEL sites Atlanta Summit, Mores Creek Summit, Trinity Mountain, and Soldier R.S. (the Camas Creek Divide was excluded since it is not located in the main part of the watershed). USGS#13190500 had much poorer correlations with precipitation and SNOTEL data because it is regulated (site located below Anderson Ranch Dam).

Linear regression equations were developed for both streamflow sites from both the precipitation and snowpack data. These regressions were based upon November through April precipitation as well as for April 1st snow water content. Appendix D contains information on these regression equations. The estimated precipitation or snow water content amount increases (due to seeding) were applied to the average values and these increases entered into the streamflow regression equations to predict the increases in average streamflow that might result from the three different seeding modes. These resulting estimated streamflow increases for the two sites were then summed to obtain the total estimated increase for these two branches of the upper Boise River. This total was also divided by the average March-July streamflow at these two sites to obtain an estimated streamflow percentage increase for each seeding mode and the combination of the three modes.

The sum of the streamflow data at these two gages is still less than the total streamflow that is derived from the Boise River Basin above Lucky Peak Dam. To resolve this under-estimate, NAWC obtained additional data from Steve Burrel (hydrologist with the IDWR), which was calculated from a gage on the lower portion of the Boise River below Lucky Peak Dam. This dataset provides estimates of the total monthly (unregulated) streamflow values for the Boise River after correcting for reservoir storage. NAWC found a very high correlation (r values exceeding 0.98) between these data and the unregulated gage #13185000 on the Middle Fork of the Boise River for the March - July period. NAWC then subtracted the 2-gage subtotal (described in the above paragraph) from the total March-July streamflow calculated (by IDWR) for the Boise River, to obtain the additional streamflow that is not represented by the 2-gage subtotal. Finally, this additional streamflow was multiplied by the average percentage increases by seeding mode and added to the 2-gage increase subtotal to obtain estimated increases in acre-feet (by seeding mode) for the entire basin. Tables 6-3 and 6-4 provides these estimated increases in streamflow, in terms of the total percentage increase and in acre-feet.

Table 6-3
Estimates of Increases in Average March-July Streamflow based upon Estimated Increases in November – April Precipitation

	Total Increase (6.8%)	Ground (2.3%)	Remote (2.0%)	Air (2.5%)
USGS#13185000	40967	13,656	12,049	15,262
USGS#13186000	31,361	10,454	9,224	11,684
2-Gage Subtotal incr	**72,328**	**24,110**	**21,273**	**26,946**
Est Additonal incr	26,902	8,967	7,912	10,022
Est Total Incr	**99,230**	**33,077**	**29,185**	**36,968**

Table 6-4
Estimates of Increases in Streamflow based upon Estimated Increases in April 1st Snow Water Content

	Total Increase (5.6%)	Ground (2.0%)	Remote (1.9%)	Air (1.7%)
USGS#13185000	33,292	11,791	11,097	10,404
USGS#13186000	26,058	9,229	8,686	8,143
2-Gage Subtotal incr	**59,350**	**21,020**	**19,783**	**18,547**
Est Additional incr	22,075	7,818	7,358	6,898
Est Total Incr	**81,425**	**28,838**	**27,141**	**25,445**

NAWC believes the results from Table 6-3 are more representative since the increases in April precipitation are ignored in Table 6-4. As a consequence, we will focus on the estimates from Table 6-3. Comparison of Table 6-1 with Table 6-3 indicates that a 5.1% increase of precipitation would result in an estimated streamflow increase of 6.8%. It has been NAWC's experience that predicted increases in streamflow from cloud seeding programs are normally higher than predicted increases in snow water content on a percentage basis. We believe this to be due to the fact that any evapo-transpiration and ground water recharge requirements are met by the non-augmented (or natural) snowpack such that increases, assumed to be produced by cloud seeding, are added to the snowpack after these base requirements are met.

It needs to be emphasized that the estimated increases in streamflow provided in Tables 6-3 and 6-4 are for an average March through July streamflow amount. The estimated increases (in terms of acre-feet) would be higher from an above normal winter and lower from a below normal winter. The reader is reminded that based upon a comparison of results from the operational program being conducted in this area by NAWC (using manually operated ground generators) with our theoretical estimates of potential increases that the operational results are higher than the theoretical estimates (refer to section 6.2.2). **Since NAWC used the theoretical estimates of increases in precipitation to estimate the increases in streamflow, we conclude that these streamflow estimates may be somewhat on the conservative side.**

6.3 Cost Estimates of Augmented/Enhanced Program

Preliminary cost estimates have been prepared for one winter season of data collection as discussed in Section 8.1. An estimate of the annual cost of augmenting the existing program that utilizes manually operated ground generators has been prepared. This augmentation would be in the form of extending the operational seeding operations by one month (April). Estimated costs of enhancements to the existing program, the use of remote generators and the use of one turbine cloud seeding aircraft have also been prepared. Costs are provided for a six-month operational period (tentatively November through April). Costs include estimates of the reimbursable expenses of seeding (e.g., seeding materials and flight hours).

6.3.1 Estimated Cost to Conduct One Winter Season of Preliminary Data Acquisition

As mentioned in Section 8.1, NAWC recommends one winter season of program specific data collection. Data of primary interest will be information on the presence, frequency and magnitude of supercooled liquid water (slw) in winter clouds over and upwind of the proposed target area and the temperature, moisture and wind structure of the lower atmosphere during winter storm periods. It is proposed that one icing rate meter be installed at a suitable location to collect the slw information and that rawinsondes (weather ballons) be launched every six hours during storm periods. A passive microwave radiometer could be added to provide more comprehensive slw measurements if additional funding is available. The radiometer and radiosonde receiver would be located at suitable locations either in or upwind of the target area. The icing rate meter would be installed at an exposed mountainous ground location that is accessible and has electrical power available. It is proposed that these systems be operated for the six-month period of November through April. The preliminary estimated costs for the three systems are as follows:

Microwave Radiometer, Icing Rate Meter and Rawinsondes

Set-up, Take-Down, Data Analysis and Reporting

Personnel		$17,000
Direct		
Land leases		$ 3,000
Travel/per diem		$ 1,000
Report		$ 750
	Total	$21,750

Six Months of Operations (Nov-Mar)

Rawinsonde Observations		$130,000
Icing Rate Meter Observations		$ 30,000
Radiometer Observations		$ 50,000
	Total	$210,000

Estimated Grand Total $233,750

Rawinsonde observations are budgeted for 120 releases during the November through April period. Radiometer observations would be acquired using a dual channel (water vapor and water liquid) microwave radiometer. The three types of observations are listed in descending order of priority. In other words, rawinsonde observations are listed as the first priority. This was done in case financial resources are not available to fund all three types of observations.

6.3.2 One Month Extension of Operational Program

Estimates for this one-month extension are provided in the following.

Estimated One Month Fixed Costs	**$9,000**
Estimated One-Month Reimbursable Costs	**$4,900**
Estimated Total	**$13,900**

6.3.3 Remotely Operated Silver Iodide Ground Generator Program

Assumptions: Six month program (Nov. – Apr.), 5 remotely controlled, ground based generators; estimated 2,000 seeding hours; local, part-time technician performing generator installation and removal, re-charging and maintenance tasks; direction of seeding activities from the contractor's headquarters; annual final report preparation including an analysis of possible effectiveness of the seeding operations, attendance at public meetings regarding the program as needed.

There would be some one-time acquisition and installation costs associated with this seeding approach. These costs are provided separately from the anticipated annual operating costs. These are rather crude first estimates.

Estimated Remote Generator Acquisition, Siting and Installation Costs

5 remote generators, acquisition costs		$150,000
Siting costs (surveys, permits, etc.)		$ 25,000
Installation costs		$ 50,000
	Estimated Total	$225,000

Annual Set-up, Take-down and Reporting Costs

Personnel		$24,350
Direct		
Equipment (generator maintenance, propane tanks)		$20,000
Mileage, public meetings		$ 1,500
Insurance		$ 2,500
Final Report		$ 1,500
	Sub-total	$25,500
	Total	$49,850

Annual Six Months Fixed Costs

Personnel		$37,500
Direct (technician travel, per diem, telephone calls, computer use charges, etc.)		$25,000
	Total	$62,500

Estimated Six Months Reimbursable Costs

Generator Usage, 2000 hours at $8.00/hr.	$16,000

Estimated Total Annual Operating Costs $128,350*

* The generator hours are estimates. Client is typically invoiced based on actual usage. Therefore the estimated total cost could be lower depending on the frequency of seedable conditions.

6.3.4 Addition of One Seeding Aircraft

Assumptions: lease of turbine engine aircraft equipped with acetone/silver iodide generators for 6 months, one aircraft pilot, base of operations established at suitable airport near target area, program meteorologist stationed at operations base (seeding decisions will be made from this location), one program meteorologist assistant, no program dedicated weather radar (NWS NEXRAD radar to be used).

Set-up, Take-down

Personnel		$17,000
Direct		
One-half month lease of aircraft		$25,000
Pilot, meteorologist per diem and travel		$ 3,000
	Sub-total	$45,000
	Total	$62,000

Six Months Operations

Personnel		$ 89,400
Direct		
Aircraft lease		$280,000
Office, hangar, computers, utilities		$ 12,000
2 vehicles		$ 10,000
pilot/meteorologist per diem		$ 25,000
	Sub-total	$327,000
	Total	$416,400

Estimated Reimbursable Costs

120 Flight hours @ $300/hr		$ 36,000
100 hours of airborne generator usage @ $80/hr		$ 8,000
	Sub-total	$ 44,000

Estimated Total Annual Operating Costs $460,400*

* The flight hours and generator hours are estimates. Client is typically invoiced based on actual usage. Therefore the estimated total cost could be lower depending on the frequency of seedable conditions.

6.4 Summary of Estimated Costs versus Estimated Increases in March-July Streamflow

Table 6-5 provides estimates of the cost of producing increases in March through July streamflow by the augmented programs. No attempt has been made to estimate the additional streamflow that might be produced by extending the operational program by one month. The estimated increases in streamflow are taken from Table 6-3, which are based upon estimates of increases in November through April precipitation. **It is beyond the scope of this report to estimate the potential value of the increased runoff.** Should such an analysis be attempted, calculations of benefit/cost ratios could be calculated. The additional water would benefit regional water supplies for agricultural and municipal use as well as hydroelectric power generation. If the value of the additional water volume to recreation, fisheries, tourism, threatened and endangered species, and downstream uses could be quantified and included, the projected value would be even greater. NAWC did publish a paper (Griffith and Solak, 2002) that provided some crude estimates of the potential value of the operational program in terms of enhanced hydropower production.

Table 6-5
Estimated Average Costs to Produce Additional
March – July Streamflow, Remote Generators or Aircraft

	Remote Generators*	Aircraft**
Ave. Cost to Produce Extra Water	$173,350	$460,400
Ave. Water Year Streamflow Increase	29,185	36,968
Cost Per Acre-foot	$5.94	$12.45

* It is assumed that a five-year program would be conducted and that the initial remote generator acquisition, siting and installation costs would be amortized equally over this five-year period ($45,000 per year).
** One aircraft may not be capable of seeding all the suitable storm events so these estimates may be somewhat optimistic.

The seeding aircraft mode could potentially be used without the remote generator mode. If so, one seeding aircraft may not be able to seed all the events that would be considered seedable from either remote generators or aircraft. If it were assumed that the aircraft could produce all of the estimated increases in streamflow under the aircraft category in Table 6-3 (36,968) and one-half the estimated streamflow amount for the remote generators (29,185/2 = 14,953), then the estimated cost would be $460,400/51,560 = $8.93 per acre-foot.

The estimated costs to achieve these increases in March through July streamflow range from $5.94 to $12.45 per acre-foot. **These estimates are for an average water year.** Costs per acre-foot would decline in above normal water years and increase in below normal water years. As stated previously, **NAWC used the theoretical estimates of increases in precipitation (rather than the higher estimates of the effects from the operational program) to estimate the increases in streamflow. We conclude that these streamflow estimates and the cost per acre-foot estimates may be somewhat on the conservative side.**

7.0 RECOMMENDED DESIGN AND OPERATIONS CRITERIA FOR ENHANCED PROGRAM (Task 4)

7.1 Proposed Target Area

The proposed target area for the UBRB winter cloud seeding program are those regions within the Upper Boise River Basin that lie above 5,000 feet MSL. This area is depicted in Figure 7.1.

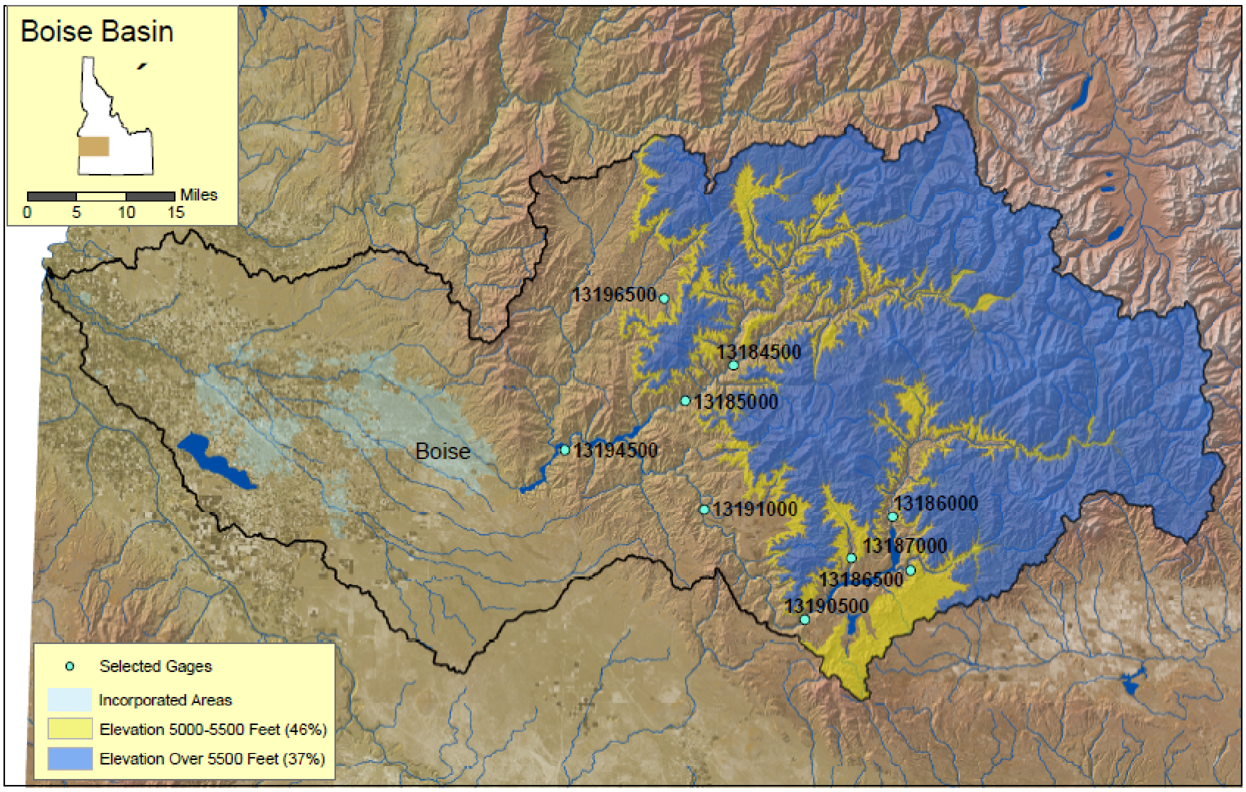

Figure 7.1 Proposed Target Area above 5000 Feet (area includes those areas outlined in yellow and blue)

7.2 Operational Period and Selection and Siting of Equipment

An operational period of November through April is recommended based upon the climatology of the area (refer to Section 4) and the likelihood of generating positive seeding effects during this period.

NAWC recommends silver iodide as the seeding agent to be used in the conduct of the enhanced UBRB program. In terms of suggested enhancements, we recommend adding remotely operated, ground based generators and airborne seeding to the existing program that utilizes manually operated ground generators.

7.2.1 Remotely Controlled, Ground Based Silver Iodide Generators

Data presented in section 6 suggests that remotely controlled, ground based seeding and airborne seeding could be used to enhance the existing program. Figure 4.10 indicates that the 700mb prevailing wind directions when remote generators are considered to be effective are predominately from the west-southwest to westerly directions. In our analysis of the potential low-level stability in the area during storm periods (section 4.2.4), NAWC did not have any data sources that could be used to estimate the depth of these low-level inversions. To be effective, the remote generators would need to be placed at locations that are above these low-level inversions in order to be effective. In this analysis we will assume that generators can be sited at appropriate locations to address this concern. The option of conducting weather balloon observations during one winter season would directly address this question.

We recommend that five remotely controlled silver iodide generators be installed at higher elevations as far upwind of the barrier crest as possible. The generators should be spaced at least 5 miles apart. Twelve approximate locations are provided in Figure 7.2 Whether suitable sites could be found in these areas is somewhat questionable due to access considerations (helicopters may be required) and the ability to obtain special use permits from the appropriate National Forest. Sites installed in these areas would likely generate increases over the Big and Little Wood River drainages should a combined seeding program involving the Upper Boise and the Upper Wood Rivers be considered in the future.

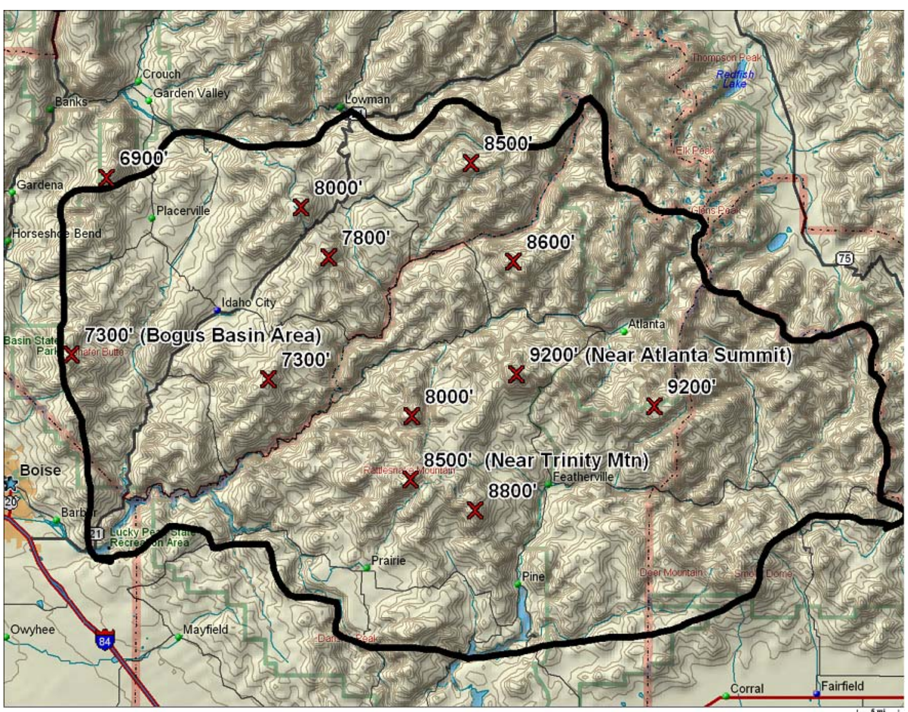

Figure 7.2 Potential Locations of Remotely Controlled, Ground Based Generators

7.2.2 Airborne Silver Iodide Seeding

Because of the proximity of the National Weather Service Boise sounding data to the seeding target area in this study, NAWC analyzed sounding and surface data to obtain estimates of cloud base height and temperature. This can be particularly useful in the consideration of aircraft seeding. Figures 7.3 and 7.4 are scatterplots showing the distribution of cloud base height and temperatures, for aircraft-only seedable periods as a subset of the distribution and for all seedable periods.

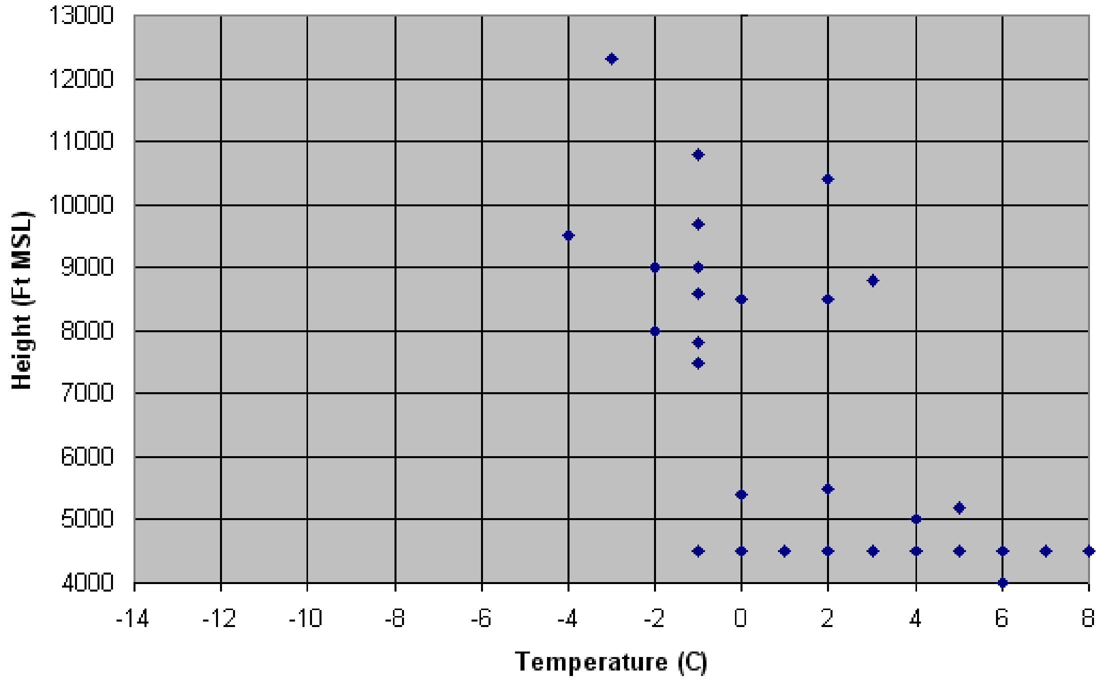

Figure 7.3 Cloud Base Height and Temperature Estimates for Aircraft-only Seedable Periods

The obvious differences between Figures 7.3 and 7.4 are understandable since the aircraft only seeding events were predicated on warm temperatures at the 700 mb level which would naturally lead to warmer cloud base temperatures.

Figure 7.3 indicates that those storm events considered seedable by aircraft experienced two types of cloud conditions. The first type is where the cloud bases are at or near ground level, which would imply that aircraft flights would be under continuous IFR conditions (i.e. the pilot relies strictly on instruments to fly the aircraft). The cloud bases under these conditions are typically warmer than freezing which could offer some potential for ice to melt off the seeding aircraft at low altitudes. The second type is one with elevated cloud bases ranging in height from approximately 8,000 to 12,000 feet MSL. A majority of these cases are associated with below freezing temperatures. This suggests that if the seeding aircraft encountered icing in clouds that the aircraft could descend into clear air above ground level where temperatures may be warm enough to melt accumulated icing on the aircraft.

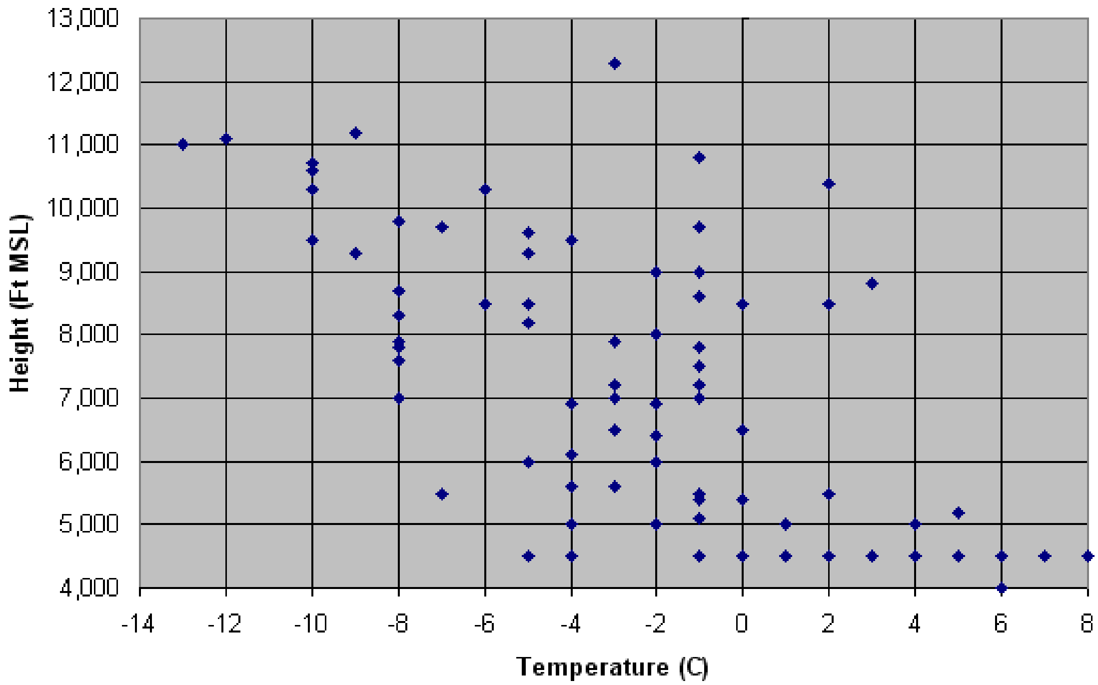

Figure 7.4 Cloud Base Height and Temperature Estimates for all Seedable Periods

Figure 7.4, for all seedable storm events, is primarily composed of cases in which the cloud bases are colder than freezing. Although we did not perform an analysis of surface temperatures at the Boise Air Terminal/Gowen Field under these seedable conditions, it is likely that in a large majority of these cases that the surface temperatures at the airport would be below freezing. Flights under these conditions would not allow the melting of aircraft icing by descending to lower flight levels.

To achieve the increases indicated for aircraft seeding assumes (in addition to those mentioned earlier concerning the number of aircraft and pilots) that the aircraft can be safely flown low enough, often enough, so that the seeding plumes impact the regions of supercooled liquid water occurring during the storm periods. The other assumption, if only using one seeding aircraft, is that the seeding plumes will spread and merge together (in the horizontal) before they reach the supercooled liquid water regions. Deshler, 1990 concludes “Achieving fairly continuous coverage along the direction of seed line advection requires seed lines to be no longer than 23 miles.”

Figure 4.11 indicates the winds at the 10,000 foot level during events deemed seedable only by aircraft will be blowing from southwesterly through west-northwesterly wind directions. The terrain in this upwind area is of low to intermediate elevations (i.e. ~ 3,000 to 6,000 feet MSL). The seeding impacts would involve the rather complex interactions of several factors: 1) timing of the seeding material coming into contact with supercooled water droplets, 2) the speed at which ice nucleation occurs (a function of the type of seeding agent), 3) the growth rate of the ice crystals (a function of the ambient temperature), and 4) wind direction and especially wind velocities from the flight level down to the surface.

Perhaps the primary reasons that airborne seeding should be considered for the UBRB program are related to the following three issues:

1. It appears from our analyses that low-level atmospheric temperature inversions are common in the Boise River valley during active storm periods.

2. Aircraft seeding may be conducted when the temperatures near crest level are too warm for silver iodide released from the ground to be effective. In other words, the aircraft can be flown at or near the -5^{0} C level in these storms, assuming there is liquid water present at these altitudes, thus having the potential for augmenting the natural snowfall in the target area.

The types of aircraft used in the conduct of cloud seeding programs vary depending upon the seeding modes selected, the time of year and safety considerations. If aircraft seeding is to be conducted, we recommend that turbine engine aircraft (e.g., Cheyenne II's) be used. This recommendation is based primarily on aircraft performance as it relates to safety considerations. As discussed in the above and in section 3.6.7, if the aircraft were to encounter extreme icing conditions, it could may not be able to descend to altitudes warmer than freezing to shed the ice due to the frequency of sub-freezing temperatures to the surface. For example, Figure 7.5 shows the average surface temperatures observed at the Town Creek site (4500' in elevation) during the seedable storm periods. These temperatures are near or below freezing during most of the months suggested to be included in the seeding program design. As a consequence, the seeding aircraft requires ample power to operate safely for adequate durations under such (airframe icing) conditions. Turbocharged, piston engine aircraft may not have sufficient power to operate safely for an extended period under these conditions. The aircraft should be equipped with a basic data collection package that would record: location, altitude, time of seeding equipment operation, temperature and supercooled liquid water content.

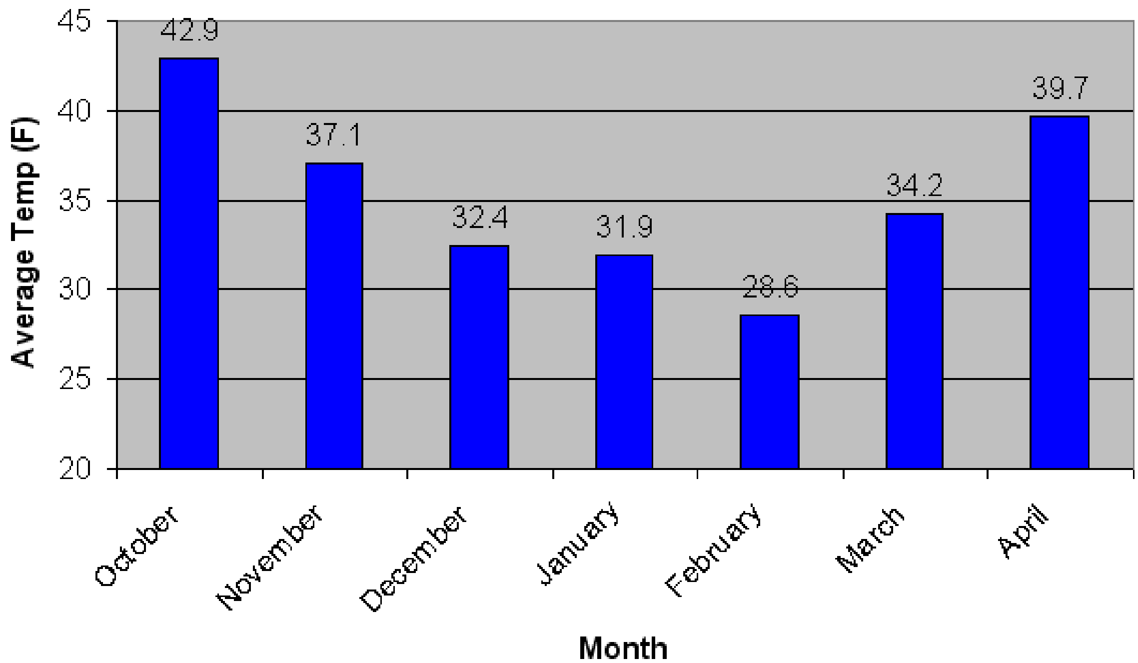

Figure 7.5 Average Surface Temperature Observed at Town Creek (4500') during Seedable Storm Periods

The logical choice for the base of operations for the seeding aircraft is the Boise Air Terminal/Gowen Field. This airport is located in close proximity to the target area and meets the general requirements for a suitable airport location which are:

- Manned for significant portions of each day (including weekends)
- Has good navigational aids including instrument approach capability
- Has an adequate length of runway
- Has lit runways at night
- Aircraft maintenance services available
- 24-hour fueling services available.

7.3 Personnel and Base of Operations

If both types of program enhancements were implemented (remote generators and aircraft), then there would be one program meteorologist, one pilot (with possibly a back-up pilot in cases with extended seeding opportunities), and one instrument technician. The base of operations would be established on or near the Boise Air Terminal/Gowen Field.

7.4 Summary of Recommended Preliminary Design

The proposed design for augmentation of the an existing cloud seeding program in the Boise River Basin can be summarized as follows:

- The target area will be the upper Boise River Basin above 5,000 feet MSL.
- The primary operational period will be November through April.
- Silver iodide will be the seeding agent.
- The existing program, that utilizes lower elevation ground based generators, will be augmented by extending the operational programs seeding period by one month. The existing program would be enhanced through the addition of remotely controlled ground based generators and aerial seeding.
- The UBRB would be operationally oriented, with the following goals: The stated goal of the program is to increase winter snowpack in the target area to provide additional spring and summer streamflow and recharge under-ground aquifers at a favorable benefit/cost ratio, without the creation of any significant negative environmental impacts.
- Due to the operational nature of the proposed program, i.e., the interest in producing as much additional water as possible, the seeding decisions would not be randomized. In other words, all suitable seeding opportunities would be seeded appropriately. In addition, there would not be an ongoing research component built into the program (beyond the first season of specialized measurements which could be used to fine-tune the design if necessary), although "piggyback" research components could be added to the core operational program if interest and additional funding from other sources is present, for example, the type of research that resulted from write-in funding to the Bureau of Reclamation for the recent Weather Damage Mitigation Program.
- Evaluations of the effectiveness of the cloud seeding program would be based upon historical target and control techniques (target and control sites with corresponding regression equations are provided elsewhere in this report), and possibly some snow chemistry analyses verifying that silver above background levels is being observed at various sampling points in the target area.
- A Qualified/experienced meteorologist should direct the seeding operations.
- If aerial cloud seeding is employed, a winter season program field office should be established near the target area. The logical location of this program office would be at the Boise Air Terminal/Gowen Field.

7.5 Operations Criteria

7.5.1 Opportunity Recognition Criteria

For the proposed WRBP program seeding criteria were developed to serve as opportunity recognition tools. Basically, these criteria have been designed to recognize the combination of weather events deemed to be "seedable". These criteria have been broken down into three different categories based upon the seeding mode to be used (ground based, low-elevation, manually operated generators; high elevation, remotely operated generators; and, aircraft). The criteria are listed in Tables 7-1 through 7-3. The criteria listed in Table 7-1 are those being used to direct the existing cloud seeding program. These criteria are included in this report for the sake of completeness.

7.5.2 Communications of Seeding Decisions

The means by which seeding decisions are communicated/implemented will be a function of the type(s) of seeding methodology employed (e.g., for manually operated ground generators, telephone calls). Remotely controlled generators typically utilize cell or satellite phones for communications. Aircraft seeding typically involves locating a program office at a suitable airport near the program area. This office would be manned by one or more program meteorologists. The pilot(s) of the seeding aircraft are also based at this office. Communications regarding aircraft missions are therefore conducted prior to take-off. Communications continue between the on-site program meteorologist and pilot via VHF or UHF radios.

7.5.3 Communications of Seeding Activities

Arrangements may be made to communicate seeding decisions in real-time to the interested parties (e.g., program sponsors) utilizing an internet site to post activities. More often summaries of seeding activities are provided on a weekly, bi-weekly or monthly basis via written reports.

Table 7-1
NAWC Generalized Seeding Criteria Developed for Use in the Intermountain West

- CLOUD BASES ARE BELOW THE MOUNTAIN BARRIER CREST.
- LOW-LEVEL WIND DIRECTIONS AND SPEEDS THAT WOULD FAVOR THE MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THEIR RELEASE POINTS INTO THE INTENDED TARGET AREA.
- NO LOW LEVEL ATMOSPHERIC INVERSIONS OR STABLE LAYERS THAT WOULD RESTRICT THE VERTICAL MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THE SURFACE TO AT LEAST THE -5°C (23°F) LEVEL OR COLDER.
- TEMPERATURE AT MOUNTAIN BARRIER CREST HEIGHT EXPECTED TO BE -5°C (23°F) OR COLDER.
- TEMPERATURE AT THE 700-MB LEVEL (APPROXIMATELY 10,000 FEET) EXPECTED TO BE WARMER THAN -15°C (5°F).

Table 7-2
Opportunity Recognition Criteria
Remotely Operated Ground Generators

1. Cloud top temperatures expected to be ≥ - 26 ^{0}C.
2. 700 mb level temperatures expected to be ≤ - 5 ^{0}C.
3. Low-level atmospheric stability moderately to very stable.
4. Low-level wind directions expected to be favorable for the transport of the seeding material over the target barrier(s).
5. Cloud bases expected to be at or below target barrier crest height.

Table 7-3
Opportunity Recognition Criteria
Aircraft Seeding

1. Cloud top temperatures expected to be ≥ - 26 ^{0}C.
2. 700 mb level temperatures expected to be ≥ - 5 ^{0}C.
3. Mid-level wind directions expected to be favorable for the transport of the seeding material over the target barrier(s).
4. Cloud bases expected to be at or below target barrier crest height.

8.0 DEVELEOPMENT OF MONITORING AND EVALUATION METHODOLGY (Task 5)

8.1 Meteorological Data Collection and Instrumentation

Specialized types of equipment, data collection and instrumentation will be needed to conduct the cloud seeding program(s). The various types of equipment or observations will include seeding devices, means of communication, information and observations used in real-time to make seeding decisions and observations used after the fact in evaluations of the effectiveness of the seeding programs. Possible observational systems that will be considered include: microwave radiometers, icing rate meters, rawinsondes, program dedicated weather radars, cloud physics aircraft, and program specific precipitation gages. <u>**There are three primary uses of or justifications for the addition of meteorological measurements or instrumentation: 1) such additions will assist in better targeting of the seeding material, 2) such additions will provide better real-time recognition of seeding opportunities, and 3) such additions will provide the means to help evaluate the effectiveness of the seeding operations.**</u>

NAWC proposes that a <u>phased data collection approach</u> be adopted in the performance of this program. The goal will be to make critical observations early in the history of the program, which may later be discontinued or replaced with more basic measurement or prediction approaches. For example, one of the primary concerns regarding the conduct of a winter orographic cloud seeding program in a new area is the frequency, magnitude and location of supercooled liquid water upwind and over the barriers in question. We propose that a ground based icing rate meter be operated at a suitable location in the UBRB target area. Figure 8.1 provides a photo of one of these units. Data from these icing rate meters provide point observations of supercooled liquid water. Recall from discussions in Section 3.1 that supercooled water droplets are the targets of opportunity in the conduct of winter orographic cloud seeding programs. NAWC has previously used an icing rate meter installed at a mountain top location located east of Salt Lake City, Utah to study icing events at that location (Solak, et al, 2005), with interesting and useful results.

A microwave radiometer could provide vertically integrated samples of the water content of the atmosphere from the surface to the top of the atmosphere but these radiometers are more costly than the icing rate meters. A microwave radiometer could be operated for one winter season in association with ground based icing rate meter to determine the degree of correlation between the two observational techniques. Figure 8.2 provides a photo of a portable microwave unit.

Figure 8.1 Icing Rate Meter

We also propose that program specific rawinsonde (weather balloon) observations be taken during storm periods during the first winter season of the program. The release location of these rawinsondes should on the western side of the upper Boise drainage at approximately 4,000 feet elevation. The main question to be answered from these releases is whether there are frequent low-level inversions during otherwise seedable storm periods. NAWC's indirect analyses suggest this is the case. These inversions would limit the usefulness of the lower elevation ground based generators. The other question that could be answered, if low-level inversions were observed, is what is the altitude of the average top of these inversions. This information would be quite useful in specifying the desired elevations of the remotely controlled generator sites. The desire would be to locate the remote generators above the average height of the top of these inversions such that the upward transport of the silver iodide seeding materials would not be restricted.

Figure 8.2 Example of a Portable Microwave Radiometer

The need for program communications will be partially dependent upon the type of seeding methodology or methodologies that are adopted. For example, if both higher elevation remotely controlled generators and seeding aircraft were utilized, there would be a need for radio, cell phone or satellite links to the remotely controlled generators. Means of communication between the pilot of the seeding aircraft and the program meteorologist would also be needed (e.g., radio). Both situations may entail some form of licensing by the Federal Communications Commission.

A variety of public information and observations will be useful in the real-time decision making on these programs. Weather observations (surface and upper-air), weather forecasts, weather warnings, prognostic charts, satellite photos (both visible and infrared), NEXRAD radar displays and predicted or observed streamflow will all be utilized. Such information is readily obtained through the internet from a variety of web sites and is therefore available to the programs at no cost. Providers of this type of information include, for example, the National Weather Service (NWS) and the Natural Resources Conservation Service (NRCS).

The need for other additional program specific observations has been considered in other studies. For example, should additional precipitation gages be installed in the potential target area? One might think that installing additional precipitation gages in the cloud seeding target areas would provide a better means of evaluating the effects of the cloud seeding. This would be true if the program design called for randomization of the seeding treatment decisions. The program design that we are recommending does not call for this randomization technique to be used since the program goals focus on maximizing the precipitation augmentation potential. As a consequence, we do not recommend that any additional program specific gages be installed. The reason that additional gages would not be useful in detecting effects of cloud seeding is that most of the precipitation episodes will be seeded. Consequently, there will not be any useful non-seeded data within the program target area to compare with the seeded data. There will be some non-seeded data but they will have built-in biases. The non-seeded events will be either very weak events with little or no seeding potential or perhaps very strong ones that are considered to have very limited seeding potential or are not seeded because seeding suspension criteria are exceeded.

Weather radars provide very useful information in terms of real-time decision making on operational cloud seeding programs. Radars that are installed specifically to support cloud seeding programs are more commonly used when cloud seeding aircraft are used on a program. This is especially true in the case of summertime programs where echo developments observed by the program meteorologist on the weather radar can be relayed to the pilot of the seeding aircraft. Such information can be useful in both identifying favorable areas for seeding as well as areas to avoid while flying (safety issues). The National Weather Service (NWS), through a modernization effort in the 1990's, installed a network of very sophisticated 10 cm wavelength weather radars throughout the U.S. These sites are known as NEXRAD (Next Generation Radar) installations. Each installation originally cost on the order of $1,000,000. Figure 8.3 provides a photo of a NEXRAD Installation. Figure 8.4 shows the array of these sites across the U.S. There are approximately 160 NEXRAD sites now in service. Each of the radars provides information on precipitation and wind speed and direction within the precipitation echoes. The radars step scans through up to 14 different elevation angles in a 5-minute period and a computer program integrates the stepped scans into a volume scan. Several very sophisticated algorithms then produce a large number of specialized displays and products from each volume scan. The maximum range for the detection of precipitation echoes is ~140 miles from each site. The NWS provides all the necessary support for these systems; operation, calibration, spare parts and maintenance. Because the NEXRAD network is important to NWS forecasting and public safety responsibilities, as well as many hydro meteorological applications and aviation safety, these radars enjoy high priority support and a resultant high degree of reliability.

The NEXRAD installation of the most interest in the conduct of the UBRB program will be the Boise site. The NEXRAD radars provide information out to ~144 miles (230 km), but the usefulness of this information declines beyond ~100 miles due to the curvature of the earth. The Boise site offers good radar coverage upwind and over the target area.

NEXRAD data are available in near real time at approximately 5-6 minute intervals through a variety of internet web sites.

Figure 8.3 Photo of A National Weather Service NEXRAD Radar Installation
(Photo courtesy of the National Oceanic and Atmospheric Administration)

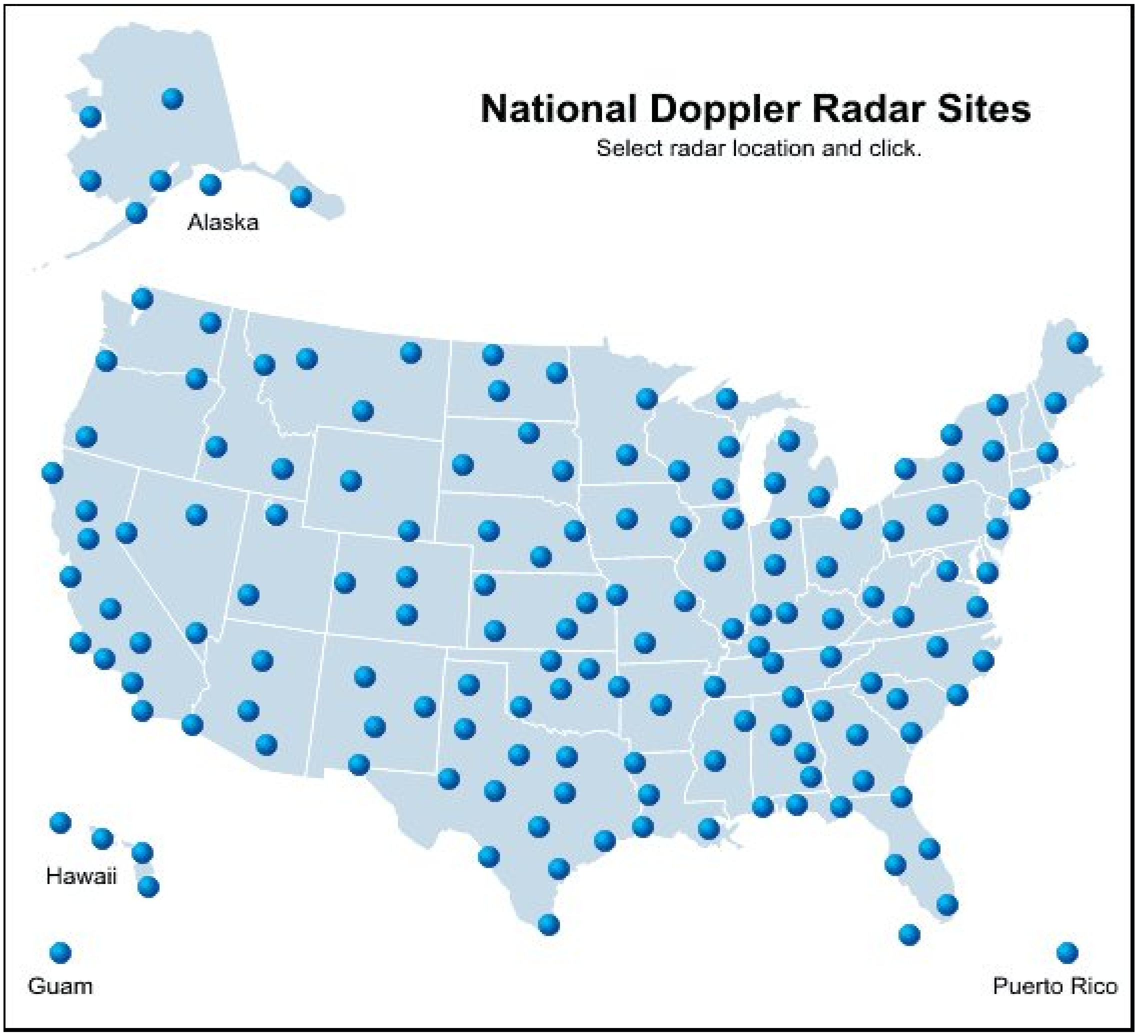

Figure 8.4 National Weather Service NEXRAD radar locations

NAWC has utilized the WeatherTap (commercial, subscription) web site extensively over the past several years to provide radar data for conduct wintertime cloud seeding programs. This web site provides a variety of useful products including: echo intensities (precipitation), echo tops, vertical profiles of wind speed and direction (the very useful VAD displays mentioned earlier) and composite echo displays that integrate radar returns from all of the 14 different elevation scans.

Given that good NEXRAD coverage is available for the proposed program area, we do not think the additional cost of providing program dedicated weather radar is justified. This recommendation is based not only on a cost consideration but also upon actual experience in which NAWC has successfully used the NEXRAD radar at Vandenberg AFB, California to help direct a winter cloud seeding program for the Santa Barbara County Water Agency and at Hanford, California to help direct seeding operations for a winter cloud seeding program conducted for the Kings River

Conservation District. These programs utilize both ground based seeding equipment and a cloud seeding aircraft.

Since NAWC has indicated that a cloud seeding aircraft may be potentially useful in the conduct of the UBRB, it is concluded that the Boise, Idaho NEXRAD weather radar would provide sufficient weather radar support to these airborne operations. Computer programs are available that can overlay the aircraft track on the most recent weather radar depiction from the Pocatello site. The program meteorologist, to provide seeding guidance and safety advisories, can relay this combined information to the aircraft pilot. In addition, systems are also commercially available that can provide surface-based radar depictions for use in-flight by the seeding aircraft aircrew.

Public observations of potential use in post program assessments of seeding effectiveness will include NWS cooperator precipitation measurements, NRCS SNOTEL and snow course measurements and USGS streamflow measurements.

8.2 Evaluation Methodology

An evaluation methodology was developed by NAWC for the area of interest in this study in the performance of an operational program for the Boise Project Board of Control that began in 1993. This methodology was described in detail in Section 5.2. This evaluation methodology is proposed to be used on the UBRB program should this program be implemented. This evaluation methodology will only provide an indicated increase. The relative contributions from the three seeding modes (ground generators, remote ground generators and seeding aircraft) to this overall increase will not be established using this evaluation methodology.

9.0 OPERATIONAL CLOUD SEEDING SUSPENSION CRITERIA (Task 6)

Seeding suspension criteria should be developed for this program. The primary concern will be suspension of seeding whenever flash flooding may occur during or following stormy periods (typically based upon issuance of such warnings by the local National Weather Service offices), or if unacceptably high streamflows may be produced during the spring snowmelt periods. These latter suspensions are typically based upon a sliding temporal scale of percent of normal values of higher elevation snow water contents. NAWC has established suspension criteria for several of the winter programs that we conduct in areas of the west, which are climatologically similar to the UBRB area.

We propose the use of the following suspension criteria in the conduct of the UBRB program, should it move forward.

Certain situations require suspension criteria to minimize either an actual or apparent contribution of seeding to a potentially hazardous situation. The ability to forecast and avoid hazardous conditions is very important in limiting any potential liability associated with weather modification and to maintain a favorable public image.

There are four hazardous situations around which suspension criteria have been developed. These are:

1. Excess snowpack accumulation
2. Rain and/or snowmelt-induced winter flooding
3. Severe weather
4. Avalanches

9.1 Excess Snowpack Accumulation

Snowpack begins to accumulate in the mountainous areas of Idaho in October and continues through April. The heaviest average accumulations normally occur from January through March. Excessive snowpack becomes a potential hazard because of the potential for excess snowmelt. The Natural Resources Conservation Service (NRCS) maintains a network of high elevation snow measurement sites in the State of Idaho, known as SNOTEL. The automated SNOTEL observations are routinely updated and available at least several times per day. The following set of criteria, based upon these SNOTEL site observations, has been developed as a guide for suspension of operations.

a. 200 % of average on January 1st
b. 180 % of average on February 1st
c. 160 % of average on March 1st
d. 150 % of average on April 1st

Table 9-1 contains the average 1971 – 2000 snow water content values in inches for the SNOTEL sites that are located in or near the proposed target area. The averages for these sites would be used to consider whether the above suspension criteria have been exceeded. For example, if the average snow water content (of the various SNOTEL sites) on February 1st of a particular season is 23.0" (58 cm) and the long-term February 1 average is 17.2", then the suspension point would be 17.2" x 1.80 = 31.0", so the seeding would not be suspended based upon this criterion. Since SNOTEL observations are available on a daily basis, suspensions (and cancellation of suspensions) can be made on a daily basis using linear interpolation of the first of month criteria.

Table 9-1
Monthly Target Area SNOTEL Snow Water Content 1971-2000 Normals in Inches

Site Name	Jan.1	Feb. 1	Mar. 1	Apr. 1
Atlanta Summit	13.4	20.1	26.2	31.9
Camas Creek Div.	5.1	9.3	11.7	11.0
Mores Crk. Summit	13.7	21.7	29.2	34.6
Soldier R.S.	5.8	9.2	12.0	10.0
Trinity Mt.	17.0	25.5	33.4	39.5
Average	**11.0**	**17.2**	**22.5**	**25.4**

Snowpack distribution with elevation, streamflow forecasts, reservoir storage levels, soil moisture content and amounts of precipitation in prior seasons are other factors of importance in seeding suspension considerations.

9.2 Rain-induced Winter Floods

There is the potential for wintertime flooding from excessive rainfall that occurs during storms with high freezing levels, particularly on top of low elevation snowpack. Every precaution must be taken to ensure accurate forecasting and timely suspension of operations during these potential flooding situations. The objective of suspension under these conditions is to eliminate the real, and avoid any perceived, impact of weather modification when any increase in precipitation has the potential of creating a flood hazard.

9.3 Severe Weather

During periods of hazardous weather phenomena associated with both winter orographic and convective precipitation systems, it is sometimes necessary or advisable for the National Weather Service (NWS) to issue special weather bulletins advising the public of the weather phenomena. Each phenomenon is described in terms of criteria used by the NWS in issuing special weather bulletins. Those of concern in the conduct of winter cloud seeding programs include:

- **Snow Advisory** - This is issued by the NWS when four to twelve inches of snow in 12 hours or six to eighteen inches in 24 hours is forecast for mountainous regions above 7000 feet. Lower threshold criteria (in terms of the number of inches of snow) are issued for valleys and mountain valleys below 7000 feet.

- **Heavy Snow Warning** - This is issued by the NWS when it expects snow accumulations of twelve inches or more per 12-hour period or eighteen inches or more per 24-hour period in mountainous areas above 7000 feet. Lower criteria are used for valleys and mountain valleys below 7000 feet.

- **Winter Storm Warning** - This is issued by the NWS when it expects heavy snow warning criteria to be met along with strong winds/wind chill or freezing precipitation.

- **Flash Flood Warnings** - This is issued by the NWS when flash flooding is imminent or in progress. In the Inter-mountain West these warnings are generally issued relative to, but not limited to, fall or spring convective systems.

Seeding operations <u>may</u> be temporarily suspended whenever the NWS issues a weather warning for or adjacent to any target area. Since the objective of the cloud seeding program is to increase winter snowfall in the mountainous areas of the state, operations will typically not be suspended when Heavy Snow or Winter Storm Warnings are issued unless there are special considerations (e.g., a heavy storm that impacts Christmas Eve travel).

Flash Flood Warnings are usually issued when intense convective activity causing heavy rainfall is expected or occurring. Although the probability of this situation occurring during the proposed operational seeding periods is low, the potential does exist, particularly during the spring months. The type of storm that may cause problems is one that has the potential of producing 1-2 inches or greater of rainfall in approximately a 24-hour period, with high freezing levels (e.g. > 8,000 feet). Seeding operations will be suspended for the duration of the warning in these cases.

9.4 Avalanches

Avalanche hazard is a factor worthy of consideration due to the amount of backcountry recreational activity in the program area. The Sawtooth National Forest Avalanche Center in Ketchum, Idaho issues avalanche information for the UBRB target area. Conditions are assessed daily during the winter months and reported to the named central locations from which daily advisories are issued. The Sawtooth National Forest Avalanche Center website can be viewed via www.avalanche.org.

The daily products typically consist of a weather summary for the preceding 24-hr period, mountain weather forecasts for the current day (and in some cases, three days), and a General Avalanche Advisory. That advisory includes an avalanche hazard rating within the widely accepted national standard range of five levels of hazard. During the latter portion of the winter season, when more spring-like conditions can occur, separate hazard ratings may be shown for morning and afternoon. The five national hazard categories and their published definitions are provided in Table 9-2. NAWC recommends temporary seeding suspensions based upon avalanche warnings that are issued for a day that is rated in either the Extreme or High category.

Table 9-2
Avalanche Danger Level Probability Distribution

Low

Natural avalanches very unlikely.
Human triggered avalanches unlikely.

Generally stable snow.
Isolated areas of instability.

Travel is generally safe.
Normal caution advised.

Moderate

Natural avalanches unlikely.
Human triggered avalanches possible.

Unstable slabs possible on steep terrain.

Use caution in steeper terrain.

Considerable

Natural avalanches possible.
Human triggered avalanches probable.

Unstable slabs probable on steep terrain.

Be increasingly cautious in steeper terrain.

High

Natural and human triggered avalanches likely.

Unstable slabs likely on a variety of aspects and slope angles.

Travel in avalanche terrain is not recommended.
Safest travel on windward ridges of lower angle slopes without steeper terrain above.

Extreme

Widespread natural or human triggered avalanches certain.

Extremely unstable slabs certain on most aspects and slope angles

Large, destructive avalanches possible.

Travel in avalanche terrain should be avoided and travel confined to low angle terrain well away from avalanche path run-outs.

10.0 EXECUTIVE SUMMARY

A brief background on the events that led to this Boise River feasibility study is provided in the following. North American Weather Consultants, Inc. (NAWC) received a Request for Proposals entitled "Consultant Services for the Upper Snake River Basin Weather Modification Feasibility Study," issued by the Idaho Water Resource Board (IWRB) in July 2007. NAWC responded to the RFP with a formal proposal (NAWC # 07-209), which was due September 4, 2007. NAWC was notified on October 26, 2007 that it had been selected to perform this work. A contract to conduct the work was finalized on January 8, 2008. NAWC completed that study in October 2008 (Griffith, et al, 2008).

NAWC received queries from the IWRB following the completion of the Upper Snake River study about extending the type of analyses developed in the Eastern Snake study to the Big and Little Wood River Basins located in central Idaho. An agreement was reached on May 5, 2009 between the IWRB and NAWC for the performance of the supplemental study. This study was completed in August (Griffith and Yorty, 2009).

Prior to the completion of the Big and Little Wood River study report IWRB personnel asked if NAWC could perform a feasibility/design study for the Upper Boise River Basin. An agreement between the IWRB and NAWC was reached on July 9, 2009 in which NAWC was tasked to perform this study.

Seven tasks were identified that NAWC would perform in the completion of the Upper Boise River Basin study:

1. Review and Analysis of the Climatology of the Target Area.
2. Review and Assessment of the Existing program.
3. Evaluate Enhancements to the Existing Program.
4. Establish Criteria for Program Operation.
5. Development of Monitoring and Evaluation Methodology.
6. Development of Operational Suspension Criteria
7. Preparation of a Final Report including an Executive Summary.

An interesting aspect of the Boise River Basin is that NAWC is already conducting an operational program in this area. NAWC has conducted a five-month program during the water years of 1992-1996, 2001-2005, and 2007-2009. A network of approximately 20 manually operated, ground based silver iodide generators have been used in the conduct of the program. Therefore, the design of the program that is considered in this study is focused upon potential means of augmenting or enhancing the existing program.

10.1 Program Goals and Scope

The stated goal of the program is to increase winter snow pack in the target area to provide additional spring and summer streamflow and to recharge underground aquifers at a favorable benefit/cost ratio without the creation of any significant negative environmental impacts.

Seeding operations are to be conducted on a non-randomized basis. Randomization is a technique often used in the conduct of research programs whereby approximately one-half of the potential seed cases are left unseeded to allow a comparison with the seeded cases.

10.2 Program Area

The Idaho Water Resources Board (IDWR) specified the area of interest to be the Upper Boise River Basin (UBRB). This area lies within portions of Boise, Camas and Elmore Counties. The IDWR noted that the upper Boise, including the North Middle and South Forks, and Mores Creek supplies 90% of the water for the lower Boise Basin. The UBRB ranges in elevation from approximately 3,000 feet MSL at Lucky Peak Dam to crest elevations of approximately 8,500 to 9,500 feet MSL between the Boise River and Big Wood River Basins. NAWC recommends that the intended target area for the UBRB program be defined as those regions in the basin that are above 5,000 feet MSL. This area is outlined in Figure 10.1.

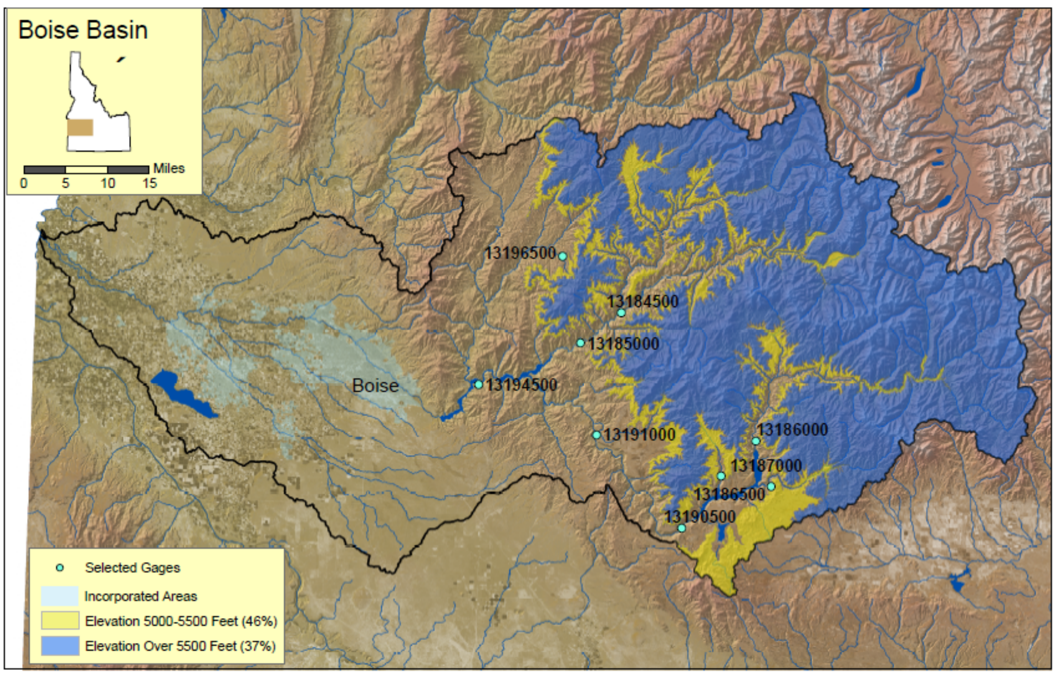

Figure 10.1 Proposed Target Area above 5000 feet (area includes those areas outlined in yellow and blue)

10.3 Preliminary Design

10.3.1 Seeding Methods and Materials

Prevailing temperature regimes favor use of silver iodide, the most commonly used glaciogenic seeding agent, as the most effective seeding material. Evaluation of representative atmospheric (weather balloon) soundings, which document the vertical structure of the winter storm environment, suggests that effective seeding can sometimes be accomplished using ground-based silver iodide nuclei generators. The results from the existing operational program support this conclusion. Given the relatively narrow mountain target barrier, use of a fast-acting silver iodide solution formulation is recommended.

The existing operational program could be augmented by extending the seeding from the current five-month program (November through March) by adding an additional month of seeding (April). Data presented in section 6 suggests that remotely controlled, ground based seeding and airborne seeding could be used to enhance the existing program. The prevailing 700 mb (~10,000 feet) wind directions when remote generators are considered to be effective are predominately from the west-southwest to westerly directions, which indicates the preferred locations of the remote generators would be west- southwest to west as far upwind of the barrier crest as possible while maintaining the highest elevations as possible. In our analysis of the potential low-level stability in the area during storm periods, NAWC did not have any data sources that could be used to estimate the depth of the low-level inversions. To be effective, the remote generators would need to be placed at locations that are above the low-level inversions. This is the reason for the recommendation that the generators be located at the highest elevations as practical.

We recommend that five remotely controlled silver iodide generators be installed. The generators should be spaced at least 5 miles apart. Twelve approximate locations were identified from which five generator sites might be selected. Whether suitable sites could be found in these areas is somewhat questionable due to access considerations (helicopters may be required) and the ability to obtain special use permits from the appropriate National Forest.

Airborne seeding with silver iodide may be conducted when the temperatures near the mountain crest height are too warm for silver iodide released from ground-based sites to be effective. Airborne seeding could also be effective in conditions where low elevation inversions exist. Assuming the ability to fly safely in the desired areas upwind of the intended target area, aircraft can be flown at a temperature level appropriate for immediate activation of the temperature dependent silver iodide nuclei. If airborne seeding is to be conducted, it is recommended that turbine engine aircraft be used. This recommendation is based primarily on aircraft performance as it relates to safety considerations, given the airframe icing that commonly occurs during seeding operations. From some analyses of the timing of the seedable events, it appears one aircraft could seed a large majority of these events (i.e., two aircraft would not be required). The suggested base of operations would be at the Boise Air Terminal/Gowen Field Airport.

10.3.2 Operational Period

The recommended seeding period extends from November through April.

10.3.3 Key Elements of the Recommended Preliminary Program Design

- The target area will be area in the upper Boise River Basin above 5,000 feet MSL.
- The primary operational period will be November through April.
- Silver iodide will be the seeding agent.
- The operational program could be augmented by extending the seeding to a sixth month (April).
- Remotely controlled ground generators and seeding aircraft would be used to enhance the existing operational program that currently uses lower elevation, manually operated ground based generators.
- The UBRB would be operationally oriented, with the following goal: **to increase winter snowpack in the target area to provide additional spring and summer streamflow and to thereby also help recharge under-ground aquifers at a favorable benefit/cost ratio, without creation of any significant negative environmental impacts.**
- Due to the operational nature of the proposed program, i.e., the interest in producing as much additional water as possible, the seeding decisions would not be randomized. In other words, all suitable seeding opportunities would be seeded appropriately.
- Evaluations of the effectiveness of the cloud seeding program would be based upon historical target and control techniques (target and control sites with corresponding regression equations).
- A qualified/experienced meteorologist should direct the seeding operations.

10.4 Potential Yield/Benefits

10.4.1 Estimated Increases in Precipitation

Analysis of the variability in storm temperature structure over the proposed target area for an eight winter season period was performed and then applied in conjunction with cloud top temperature partitioned seeding results from a research program in Colorado (Climax) to estimate the anticipated seeding effects for the UBRB. The analysis applied the varying Climax seeding effects within cloud top temperature categories according to their seasonal occurrence in the UBRB cloud top temperature data that were identified during a multi-year period. The resulting estimated percentage of seedable events was 21%. Using these results, the multi-season average estimated increases were calculated for the ground and airborne seeding modes. These increases were then applied to the April 1st snow water contents to estimate the potential average increases in snow water contents (Table 10-1) for the upper Boise River Basin, listed by seeding mode. Similar calculations were made for increases in November through April precipitation (Table 10-2).

Table 10-1 Estimates of Average Increases in April 1st Snow Water Content by Seeding Mode (Based on November-March storm periods)

Site	Apr 1 SWE	Total Increase (4.7%)	Ground (1.7%)	Remote (1.6%)	Air (1.5%)
Atlanta Summit	31.9	1.50	0.54	0.51	0.48
Soldier R.S.*	10.0	0.47	0.17	0.16	0.15
Mores Creek Sum	34.6	1.63	0.59	0.55	0.52
Camas Creek Div*	8.2	0.39	0.14	0.13	0.12
Trinity Mtn	39.5	1.86	0.67	0.63	0.59
Average	**24.84**	**1.17**	**0.42**	**0.40**	**0.37**

Table 10-2 Estimates of Average Increases in November-April Precipitation by Seeding Mode

Site	Nov-Apr Precip	Total Increase (5.1%)	Ground (1.7%)	Remote (1.5%)	Air (1.9%)
Atlanta Summit	33.3	1.70	0.57	0.50	0.63
Soldier R.S.	15.3	0.78	0.26	0.23	0.29
Mores Creek Sum	35.0	1.79	0.60	0.53	0.67
Camas Creek Div	15.0	0.77	0.26	0.23	0.29
Trinity Mtn	41.0	2.09	0.70	0.62	0.78
Average	**27.92**	**1.42**	**0.47**	**0.42**	**0.53**

10.4.2 Estimated Increases in Streamflow

The estimated increases in snow water content (April 1st) and precipitation (November through April) were then used to estimate the potential average increases in March through July surface runoff based upon the three different seeding modes. Tables 10-3 and 10-4 provide these results.

Table 10-3 Estimates of Increases in Average March-July Streamflow based upon Estimated Increases in April 1st Snow Water Content

	Total Increase (5.6%)	Ground (2.0%)	Remote (1.9%)	Air (1.7%)
Increase in AF				
USGS#13185000	33,292	11,791	11,097	10,404
USGS#13186000	26,058	9,229	8,686	8,143
2-Gage Subtotal incr	**59,350**	**21,020**	**19,783**	**18,547**
Est Additional incr	22,075	7,818	7,358	6,898
Est Total Incr	**81,425**	**28,838**	**27,141**	**25,445**

Table 10-4
Estimates of Increases in Average March-July Streamflow based upon Estimated Increases in November – April Precipitation

	Total Increase (6.8%)	Ground (2.3%)	Remote (2.0%)	Air (2.5%)
Increase in AF				
USGS#13185000	40967	13,656	12,049	15,262
USGS#13186000	31,361	10,454	9,224	11,684
2-Gage Subtotal incr	**72,328**	**24,110**	**21,273**	**26,946**
Est Additonal incr	26,902	8,967	7,912	10,022
Est Total Incr	**99,230**	**33,077**	**29,185**	**36,968**

Data from Tables 10-3 and 10-4 suggest that the amount of average additional March-July streamflow being produced by the existing program ranges from 28,383 to 33,077 acre-feet. The estimated increase in average March through July streamflow achieved by extending the seeding program into the month of April is 4,300 acre-feet. The cost per acre-foot for this time extension is estimated to be $3.23 per acre-foot. **Furthermore, data from these tables suggest that the amount of average additional March-July streamflow that could be produced by adding remotely controlled ground generators and aircraft seeding range from 52,586 to 66,153 acre-feet.**

The reader is reminded that based upon a comparison of results from the operational program being conducted in this area by NAWC (using manually operated ground generators) with our theoretical estimates of potential increases suggest that the operational results are higher than the theoretical estimates. **Since NAWC used the theoretical estimates of increases in precipitation to estimate the increases in streamflow, we conclude that the estimated streamflow increases may be somewhat on the conservative side.**

10.5 Cost Considerations

Table 10- 5 provides estimates of the cost of producing increases in March through July streamflow by the two alternate seeding modes (remote generators and aircraft). The estimated increases in streamflow are taken from Table 10-4, which is based upon estimates of increases in November through April precipitation. The estimated cost per acre-foot of additional runoff ranges from $5.94 to $12.45**. It is beyond the scope of this report to estimate the potential value of the increased runoff.** Should such an analysis be attempted, estimations of benefit/cost ratios could be calculated. The additional water would benefit regional water supplies for agricultural and municipal use as well as hydroelectric power generation. If the value of the additional water volume to recreation, fisheries, tourism, threatened and endangered species, and other downstream uses could be quantified and included, the projected value would be even greater.

Table 10-5
Estimated Average Costs to Produce Additional March – July Streamflow, Remote Generators or Aircraft

	Remote Generators*	**Aircraft****
Ave. Cost to Produce Extra Water	$173,350	$460,400
Ave. Mar. – July Streamflow Increase	29,185	36,968
Cost Per Acre-foot	$5.94	$12.45

* It is assumed that a five-year program would be conducted and that the initial remote generator acquisition, siting and installation costs would be amortized equally over the five-year period ($45,000 per year).
** One aircraft may not be capable of seeding all the suitable storm events so these estimates may be somewhat optimistic.

The estimated costs to achieve these increases in March through July streamflow range from $5.94 to $12.45 per acre-foot. **The values in Table 10-5 are for an average water year.** Costs per acre-foot would decline in above normal water years and increase in below normal water years.

10.6 Concluding Remarks

This feasibility/design study has determined that extending the time period being seeded and adding enhancements to the operational program (adding ground based remote generators and a seeding aircraft) could augment a current winter cloud seeding program being operated in the upper Boise River Basin. Augmenting the current operational seeding program to include the month of April is estimated to produce an average increase in March-July streamflow of 4,300 acre-feet at an estimated cost of $3.23 per acre-foot. The enhanced program has the potential to increase the November through April precipitation by 3.4%, which is estimated to produce a 4.5% increase in March through July runoff in an average water year. The resultant estimated increase in March through July runoff is 66,153 acre-feet in an average water year. The estimated cost to achieve these increases in March through July streamflow is $9.58 per acre-foot.

NAWC recently completed a feasibility/design study similar to this study for the Big and Little Wood River basins (Griffith and Yorty, 2009). Since the Big Wood River Basin is adjacent to the upper Boise River Basin, the cloud seeding enhancements mentioned in this study would also impact the Big Wood River Basin and to a lesser extent the Little Wood River Basin. As a consequence, the expense to add these enhancements to the upper Boise River Basin could perhaps be shared between the Boise River and Wood River interests in some prorated fashion.

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APPENDIX A

REVIEW AND SUMMARY OF PRIOR STUDIES AND RESEARCH

1.0 REVIEW AND SUMMARY OF PRIOR STUDIES AND RESEARCH

When considering the feasibility of a proposed activity, in this case the cloud seeding of winter storms to augment snowpack and resultant runoff, it is good practice to review earlier similar efforts. This can take the form of individual program reviews, but can also benefit greatly from consideration of the statements or policies of professional societies or associations concerned with such issues. In this section, we do both, beginning with the generalized indications at the organizational level, and then summarize program-specific indications from particularly relevant efforts within the realms of field operations and research. The various indications are then summarized according to what we consider to be the key relevant questions involved in a credible assessment of winter snowpack augmentation feasibility for eastern Idaho.

1.1 Relevant Winter Weather Modification Research Programs

This section contains summaries of findings from some of the weather modification research programs that we deem relevant to the design of the Eastern Snake River Basin Program (ESRBP).

1.1.1 Utah Research Programs

The Utah State government, specifically the Division of Water Resources, has been highly supportive of weather modification research in the State of Utah. Over a period of more than three decades, the State has sponsored or co-sponsored such activities, including cooperative efforts with the U.S. Bureau of Reclamation (USBR) and the National Oceanic and Atmospheric Administration (NOAA).

1.1.1.1 Utah State University

Some early investigations in Utah are reported in Hill (1980). Via analyses of supercooled water concentrations, precipitation records, aircraft icing reports and upper air soundings, it was found that winter orographic clouds over windward slopes of mountains in northern Utah, with cloud-top temperatures between 0^0 C and -22^0 C, are primarily composed of supercooled liquid water (SLW) and therefore offer high modification potential. The SLW concentrations were found to be correlated with updraft velocity. The potential precipitation yield is dependent on the SLW flux over the barriers. Hill concluded that high seedability was associated with 1) postfrontal conditions, when a) the cross-barrier flow is strong, b) high level subsidence is occurring, c) moisture remains high at mountaintop levels; and 2) weak low-level moisture systems with strong airflow and perhaps subsidence aloft. Hill also speculated that, in the absence of convection, seeding opportunity is limited, especially in well-developed cyclonic systems.

1.1.1.2 NOAA/Utah Atmospheric Modification Program (AMP)

Utah was one of two original states selected by the National Atmospheric and Oceanic Administration (NOAA) for the conduct of research superimposed on an on-going operational program (North Dakota was the other state). Research in Utah began in 1981 (Golden, 1995). A variety of remote sensing and in situ observations have been acquired in this research program in Utah in/over a variety of mountain ranges (Wasatch Plateau, Wasatch Range and Tushar Range). Some key results from the Utah Atmospheric Modification Program (AMP) are summarized in the following. Much of the work done in the 1990's is summarized in Super (1999).

- Supercooled Liquid Water

Microwave radiometer, aircraft cloud physics and ridge-top ice detector observations have indicated that supercooled liquid water commonly occurs in Utah winter storms. The amounts of liquid water are oftentimes not large but liquid water is frequently present for significant periods during the passage of winter storms. The supercooled liquid water is concentrated along the windward slopes of the Utah mountain barriers and frequently occurs at relatively low levels in the storms (i.e., near or below the crest height). Some of the liquid water occurs at relatively warm (e.g.,>-5^{0}C) temperatures. (Super and Huggins, 1993; Huggins, 1995).

- Trajectories of Ground Releases of Silver Iodide Seeding Material

In the Utah research conducted in the 1990's, increasing attention was focused upon observing the trajectories and estimated concentrations of ground releases of silver iodide seeding material. Primary observations included ground based and aircraft based National Center for Atmospheric Research (NCAR) acoustic counters and sulfur hexafluoride (SF_6) real-time analyzers.

A ground based NCAR counter (Langer, 1973) located at the 2.2 km elevation in Big Cottonwood Canyon in the Wasatch Front Mountains during the 1989-90 winter season, detected silver iodide nuclei released from two silver iodide generators located further down the canyon. One or both generators were activated during 13 separate storm events. Silver iodide nuclei were detected in significant concentrations on each of the 13 events (Super and Huggins, 1992).

SF_6 and/or silver iodide releases from valley locations upwind of the Wasatch Plateau were detected by aircraft and/or ground based analyzers over or along the ridgeline of the Wasatch Plateau in a number of different cases (Griffith, et al., 1992; Super, 1995). Other cases did not indicate the transport of seeding material released from valley generators over the Wasatch Plateau. The latter cases normally corresponded with the presence of low-level stable layers or temperature inversions and light surface winds. Some cases apparently demonstrated a "pooling" of silver iodide nuclei under inversion conditions followed by the transport of these nuclei over the barrier with the passage of some weather feature. The spread of seeding plumes, as evidenced by SF_6 analyzer and NCAR counter measurements, is suggested as occurring in a sector on the order of 15^0 to 25^0 (Griffith, et al**,** 1992; Super, 1995).

Calculations of the spacing of valley generators to obtain overlap of plumes over the Wasatch Plateau suggest spacing on the order of 4 to 5 km. Tests of remotely controlled silver iodide generators located part way up the windward side of the Wasatch Plateau indicated more reliable transport of silver iodide material over the Wasatch Plateau than that obtained from valley based generators.

Utah research reported by Heimbach, et al, 1998) and summarized in Super, 1999 indicated that, when surface-based temperature inversions existed, valley released seeding material was sometimes transported up and over the intended mountain target area, likely by the action of gravity waves induced by an upwind mountain range. Such gravity wave effects can be migratory.

The Utah research efforts indicate that in that a large proportion of the investigations aircraft cannot (for safety reasons) reliably fly low enough relative to the underlying rugged terrain to sample the SLW pool and the ground-released seeding plumes. An extremely important finding is that the two (both the SLW and seeding material) are commonly <u>commingled</u> relatively (and enticingly) close to the mountainous terrain, but it is difficult to obtain in-situ measurements of the admixture.

- Propane Seeding

The results of additional experimentation on the Wasatch Plateau during the winter of 2003-04, randomized seeding trials testing the effectiveness of mid-mountain releases of unburnt propane, are reported in Super and Heimbach, 2005. Using a seeding site already demonstrated in earlier research to provide routine targeting of target gages a short distance (2.0 – 6.5 km) downwind of the seeding site, 98 short duration experimental units (EU's) and 47 randomized pairs were obtained and subjected to testing. Some of their results include:

- Statistical tests of the 98 EU's without partitioning were strongly suggestive of a seeding effect; increased snowfall at the three target gages. Results for a gage farther downwind were inconclusive.

- A partition focused on southwest flow cases was also strongly suggestive of seeding increases.

- There were suggestions that seeding may have been more effective when SLW cloud was detected, when seeding plume temperatures were warmer, when wind speeds were lighter, and when natural snowfall was lighter. The evidence for these relationships was inconclusive, requiring a larger EU sample size for rigorous testing.

- Inconclusive indications of up to 25% more snowfall for seeded EU's in one wind direction partition were reported.

- Statistical pair testing provided an average seeded EU increase of 0.014 in h^{-1}.

- The authors speculated that, via extrapolation of these suggestive, small area seeding coverage indications to a much larger area, snowfall increases of the order of 10% might result. Note: This would require installation and operation of a very large number of propane seeding sites, given the small horizontal dispersion possible, since the dispensers must be located quite close to the barrier summit in this particular location. This is an important point, since narrow barriers are typical of Utah's mountain ranges and the Salt River and Wyoming Ranges.

- Ground Generator Effectiveness

Tests were conducted on Montana State "Skyfire" and NAWC manually operated silver iodide generators. These tests were conducted at the Colorado State University Cloud Simulation Laboratory (Demott et al**,** 1995). These tests indicated an improvement in the performance of the NAWC generator over earlier tests conducted at the same facility in 1978 and 1981. This improvement was most noticeable at the warmer temperature ranges of -6^0 to -8^0 C. The improvement in efficiency was apparently related to some minor modifications made to the burn chamber and nozzle on the NAWC generator.

- Mesoscale Modeling

An application of the Clark Mesoscale model (Clark, 1977) has been made to the Utah Atmospheric Modification Program (AMP) Wasatch Plateau studies (Heimbach, et al**,** 1997; Holroyd, et al**,** 1995). The model appears to provide reasonable simulations of plume transport with some under prediction of plume concentrations in two different cases.

- Observations of Enhanced Ice Crystal Production

Some of the Utah AMP research cases sampled with cloud physics aircraft have indicated enhanced ice crystal production within the silver iodide plumes (Holroyd, et al**,** 1995; Super, 1995). Linkages of these increased ice crystals to fallout to the ground have not been adequately documented due in part to the inability to fly the aircraft near ground level in storm conditions over the Wasatch Plateau. There are limited indications of increases in precipitation measured at ground level in some of these cases.

- Application of Utah AMP Results to the Utah Operational Seeding Programs

The results from the focused research programs support the Utah operational seeding conceptual model. This is an important verification of what was assumed to be true of Utah storms based upon observations made in other geographical areas. Some refinements were made to the operations programs based on these findings.

Transport of valley released silver iodide/SF_6 over Utah mountain barriers has been documented. Since the supercooled liquid water is predominately located at low levels on the upwind slopes of mountain barriers and the generators are located in valleys upwind of these barriers, the silver iodide nuclei are encountering the preferred supercooled liquid water formation zones. In some cases, valley released silver iodide/SF_6 is not transported over the mountain barrier. These cases generally occur when there are low-level atmospheric inversions. An interesting observation from some cases was the indications that nuclei "pool" under these conditions, and are sometimes subsequently scoured from the valley and transported over the barrier with the passage of a synoptic-scale weather feature. This might suggest that valley generators should be operated under trapping inversions ahead of the passage of synoptic features. NAWC seeding criteria have typically precluded operations under these conditions.

Location of manually operated ground generators at the mouths of canyons on the windward slopes of target barriers may offer a preferred location for transport of silver iodide nuclei over the barrier when transport from valley locations is ineffective.

The plume spread from ground based releases of silver iodide and SF_6 (15^0 to 25^0) suggest that generators should be located at a spacing of 4 to 5 km apart upwind of the barrier in order to achieve plume overlap.

Remotely controlled generators may be effective during periods when valley based generators are not effective. The addition of such generators in high yield, high water value locations could offer an improvement to the current Utah operational program. Such operations are substantially more expensive than valley based networks, thus the restriction of such remote generators to high yield/high water value target locations. NAWC has installed manually operated silver iodide generators at higher elevation areas where local residents can be located to operate the units.

The improvement in efficiency of the NAWC manual silver iodide generator, as documented in the CSU tests, is an important result. The supercooled liquid water detected in Utah winter storms is frequently in the 0^0 to -10^0C range. It is in the -6^0 to -10^0C range that the recent CSU tests indicated improved efficiency over earlier tests.

Information from the Utah AMP suggested higher concentrations of seeding material and faster acting nuclei are desirable. A change has been made from a 2% to a 3% (by weight) mixture of silver iodide in acetone, along with sodium iodide and para-dichlorobenzene, so the seeding plumes now consist of silver chloro-iodide. The change to a solution using sodium iodide and para-dichlorobenzene will produce nuclei that react much faster (a condensation/freezing mechanism) than the previous formula that used a silver iodide and ammonium iodide solution, which produced nuclei that reacted slowly through a contact nucleation mechanism (Finnegan and Pitter, 1988). The density of seeding generators has been increased, further increasing the seeding material concentrations.

1.1.2 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 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%, with a high probability that the differences were not due to chance. Evidence was found for greater increases 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, et al, 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 seed effect. The Climax results regarding cloud-top temperature influence on seeding effects, along with similar indications from other programs, led to the recognition of a cloud-top "temperature window" for seeding effectiveness (Grant and Elliott, 1974).

1.1.3 Colorado River Basin Pilot Program (CRBPP)

A five-year randomized cloud seeding experiment was conducted by the U.S. Bureau of Reclamation offices located in Denver, Colorado (USBR) 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 24hr blocks of precipitation data from 71 experimental treated days and 76 experimental control days found no significant difference between precipitation, gage-by-gage, on seeded and unseeded days. However, an *a posteriori* analyses based on shorter (6hr) 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 ~10-12%. The results of the 24hr block analysis may have been negatively affected by seeding material targeting difficulties during the more stable storm phases (Elliott, et al, 1976).

Microphysical studies within the CRBPP showed that supercooled liquid water was generally found in three regions. One was located slightly upwind of the mountain barrier, one was located ~15-20 km upwind of the mountain barrier, and a third associated with an initial rise in the topography ~60-70 km upwind of the barrier. Their studies showed little or no SLW development during stable storm phases, but frequent SLW development in the neutral-unstable phases.

1.1.4 Colorado Orographic Seeding Experiment (COSE)

Researchers from Colorado State University conducted investigations in the Park Range of northwestern Colorado during the winter of 1981-82, in a program named the Colorado Orographic Seeding Experiment. The 1981-82 field campaign was a much expanded version of a field effort that was conducted during the winter of 1979-80. Airborne measurements were conducted during the 1979-80 season. The emphasis of COSE was to determine the natural physical structure of the cloud systems that affect the region toward establishment of a sound weather modification hypothesis. For that reason, no seeding was done prior to or during any of the study period storm systems. Key findings from the experiments are summarized in Rauber, et al (1986) and Rauber and Grant (1986). In 1981-82, the full suite of observations involved a scanning dual-channel microwave radiometer and supporting measurements including vertically pointing short wavelength radar, mountaintop liquid water measurements, low and high altitude measurements of ice crystal rime characteristics, rawinsonde data, and precipitation intensity measurements. Storm systems subjected to intensive case studies included prefrontal and frontal storms, postfrontal storms and orographic storms, with a particular emphasis on development of conceptual models of the structure and evolution of liquid water fields in a variety of storm situations.

Cloud top, cloud base and zones of strong orographic lift were identified as regions in stratiform systems where SLW production can occur, i.e., when the condensate supply rate exceeds the diffusional growth rate of the ice crystals present in the volume. In the aforementioned Rauber articles, SLW was found to occur in all stages of most of the storms studied, but temporal variations in the magnitude of the SLW were significant. SLW was most consistently present in relatively shallow cloud systems with warm (>-22^0C) cloud top temperatures and low precipitation rates. From a COSE case study reported by Sassen (1984), a deep, cold-topped storm system was found to rather consistently show the presence of SLW, leading that article's author's statement: "This raises, then, the question of the seedability of this type of storm from the standpoint of weather modification practices. On the basis of cloud-top temperature criteria, this storm would not have been a candidate for seeding… Nonetheless, in view of the documented presence of supercooled liquid water, it may be worthwhile to reexamine the criteria applied to this type of deep cloud system." Note: Similarly, analysis by NAWC of mountain-top ice detector measurements in Utah during the winter of 2003-04 (Solak, et al**,** 2005) found several deep, cold storms exhibiting SLW production considered adequate for seedability.

1.1.5 Grand Mesa, Colorado

The following is excerpted from a USBR report entitled *The Feasibility of Operational Cloud Seeding in the North Platte River Basin Headwaters to Increase*

Mountain Snowfall (2000). The excerpt is from Appendix A of the report, prepared by Arlin B. Super.

"Holroyd, et al (1988) discussed the results of several airborne plume tracking experiments with high altitude ground-based AgI seeding generators on the Grand Mesa of western Colorado. Sampling was done under a variety of cloud, wind and stability conditions. Ground releases were made from different sites, ranging from 650 to 2,300 feet below the 10,500 ft mesa top. Instantaneous plume widths were almost always within a factor of two of the 15-degree median angle. The instantaneous plumes meandered through a wider angle with a median of 38 degrees. With a single exception, plumes were confined to within 2,600 ft of the Mesa top, and the median vertical extent was about 1,800 ft. These results were in close agreement with earlier observations from the Bridger Range of Montana. Both mountain barriers rise about 5,000 ft above upwind valleys.

Super and Boe (1988) presented various airborne observations for two of the cases discussed by Holroyd et al (1988). They showed that the ice crystal concentrations and estimated snowfall rates were markedly increased about 2000 ft above the mesa top approximately 3.7 mi downwind from the high altitude AgI generator."

These findings provide useful information regarding seeding plume horizontal spread and vertical rise for comparison with the spatial distribution of SLW noted elsewhere in this section.

1.1.6 <u>Wyoming</u>

As part of a 2005 weather modification feasibility study conducted for the Wind River Range and Medicine Bow/Sierra Madre Ranges in Wyoming, investigators from NCAR conducted a number of modeling trials. The results and implications for seeding program design appear in the report prepared by Weather Modification Inc., for the Wyoming Water Development Commission (Weather Modification, Inc., 2005).
A few key points, relevant to the current feasibility work include the following:

- SLW associated with orographic lifting was strongly linked to the upwind side of the mountain barriers and the amount of SLW available for seeding is tied to the strength of the cross-barrier wind component.
- Tracer/seeding material released on the upwind side of the mountain barriers was shown as spreading horizontally and being lofted over the barriers, with a vertical depth of less than 500 m above the sloping terrain.
- Gravity waves and associated SLW regions were evident, forming in lines in the lee of the mountains orthogonal to the wind direction.
- Ground-based generators should be used to target the SLW associated with orographic lifting, with the understanding that the vertical depth of the seeded plumes, in the absence of convection, would be limited to about 500 m above the terrain.

- Aircraft could be used to seed the SLW above 500 m AGL, assuming the ability to fly safely relative to the underlying terrain. Aircraft could also be used to seed the SLW associated with gravity waves.

Some interesting and relevant results from aircraft observations over the Snowy Mountains in southern Wyoming were presented at the Joint AMS/WMA 17th Conference on Planned and Inadvertent Weather Modification in April 2008 (Geerts, 2008). A downward-looking radar onboard a research aircraft operated by the University of Wyoming provided detailed data showing turbulent vertical mixing in the planetary boundary layer during stormy conditions in 2006. The measurements indicated vigorous upward and downward vertical motions in the lowest 1000 meters above ground level over the windward mountain slopes on several flight days. In such updraft areas, snow can be generated rapidly. These findings suggest very good lofting of ground-based seeding material releases, such that the seeding materials can affect the precipitation process.

Acoustic ice nucleus counter observations in the Wyoming research program, reported by Boe (2008), documented seeding material plume meander in light wind conditions. These preliminary indications support upslope transport of ground-based seeding plumes and considerable horizontal meander under certain atmospheric conditions during storm occurrences.

1.1.7 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 ~15% 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).

1.1.8 Nevada/Desert Research Institute Programs

Cloud seeding has been conducted in the Lake Tahoe area in the Sierra Nevada since the 1960's. The Desert Research Institute (DRI) has conducted both operational and research programs in this area. The purposes of the research programs have varied. One of the significant developments pioneered by DRI has been in snow chemistry. One of the accomplishments in recent snowpack augmentation research is the establishment of the direct link between the seeding activity and the water reaching the ground in the form of snow. The mm/hr increases in precipitation caused by silver iodide seeding have been documented several times in the reviewed scientific literature between 1988 and 1999. The link has been established by physical and chemical techniques. The snow precipitated at particular targeted sites is connected directly to the seeding material and to concurrently released chemical tracers in that snow. The advantage of this snowpack sampling work is that the scientists are dealing with solid-state precipitation that can be sampled during and after storm events and stored in the frozen state until analyzed. The methodologies used to establish this direct linkage have been described by Warburton, et al. (1985, 1995a,b, and 1996), Chai et al. (1993), Super and Holroyd (1997), and McGurty (1999). DRI has also used remote measurements (e.g., microwave radiometers) to study the "seedability" of winter storms. Other recent work at DRI has included the development of sophisticated atmospheric models to study the evolution of features of interest (e.g., supercooled liquid water) and the predicted transport and diffusion of ground released silver iodide seeding material.

1.1.9 University of Wyoming (Elk Mountain)

The University of Wyoming, Department of Atmospheric Sciences was involved in cloud seeding research in the 1960's and 1970's. A majority of this research was conducted in "cap" clouds that often occur over Elk Mountain located in south-central Wyoming. Observations were made of ice crystal and ice nuclei concentrations (Auer, et al, 1969), the presence of surface released silver iodide plumes, cloud droplet concentrations and cloud condensation nuclei (Black, 1980), ice crystal development using cloud physic aircraft (Cooper and Vali, 1981), precipitation efficiencies based upon aircraft measurements (Dirks, 1973), and condensation-freezing ice nucleation (Kelly, 1978). Whether the results obtained from this interesting research conducted in "cap" clouds are representative of larger scale winter cloud systems in Wyoming is open to question. Certainly some of the information would likely be the same in either situation. For example, the finding that ground released silver iodide plumes seldom rise to heights greater than 1500 feet (450 m) above the surface and the dispersion angle of such plumes being on the order of 10^{0} is similar to other studies conducted in Colorado and Utah.

1.2 Relevant Operational Programs

A substantial number of winter operational cloud seeding programs have been conducted in regions of the western U.S. that have relevance to the proposed ESRBP. These are largely purely operational programs, i.e., the seeding is done on a non-randomized basis. Nonetheless, mathematical evaluations (estimations of seeding effects) have been performed for essentially all of them. Further, some have included research components during at least some of their duration.

1.2.1 Utah Power and Light

A winter snowpack augmentation seeding program was conducted by NAWC for Utah Power & Light (UP&L), focused on portions of the Bear Lake watershed, including the Thomas Fork and Smiths Fork region of Wyoming. The program used ground-based solution-burning AgI generators and was conducted during the periods of 1955-1970, 1980-1982, plus 1989 and 1990. A 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-program (statistical base period) years and the subsequent seeded and embedded not-seeded years. The double mass plotting technique is a tool frequently used in engineering circles as a means of detecting changes that may occur between two variables. That plot is shown in Figure 1.1. A distinct and sustained upward break is seen in 1955, the season marking the start of seeding operations. The trend line breaks downward during the non-seeded years in the 1970's, then upward again corresponding with the resumption of seeding operations for the winter of 1979-1980. The latter upward (seeded) slope returns to that of the earlier seeded period. The combined statistical and double-mass plot indications are quite compelling indications of an increase in precipitation in the target area that can be attributed to the cloud seeding activities.

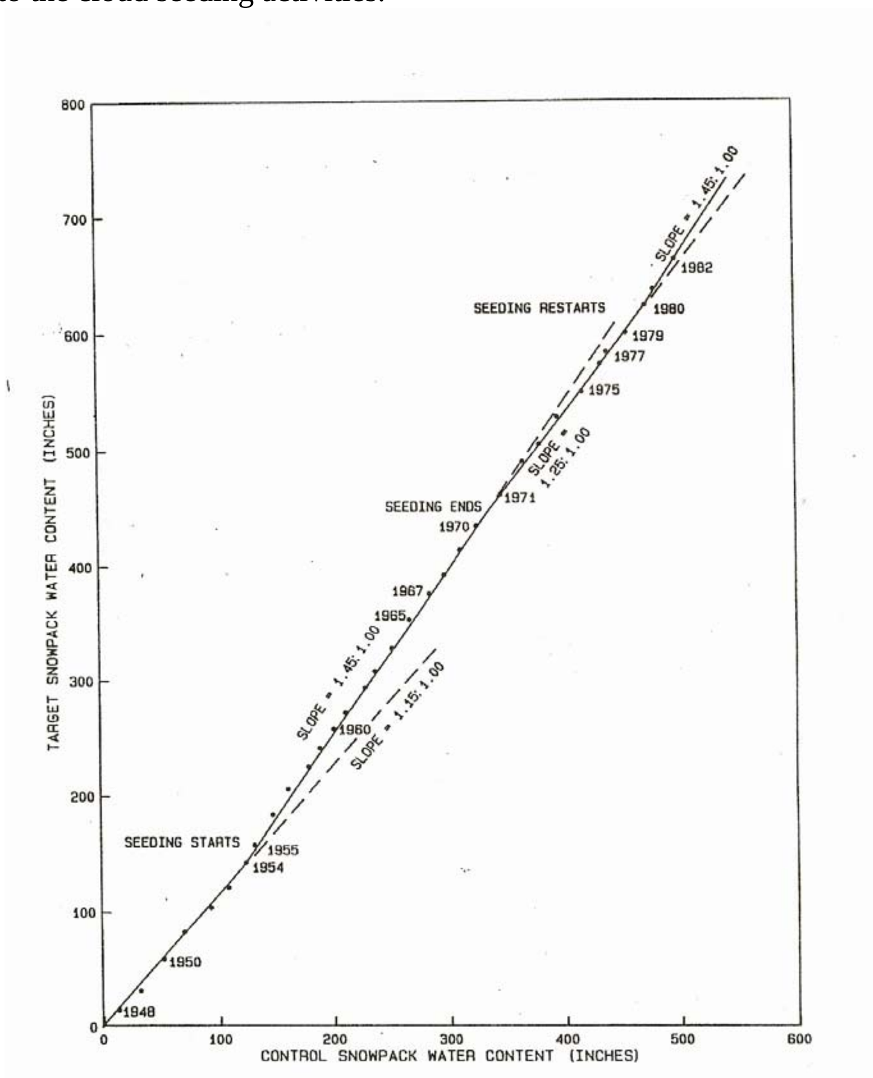

Figure 1.1 Double Mass Plot for UP&L Program

1.2.2 Boise River

NAWC has operated an operational cloud seeding program for the upper 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 are of average seasonal increases of the order of 5% to 8% (Griffith, et al, 2005).

A peer reviewed paper (Griffith and Solak, 2002) attempted to provide a rudimentary economic assessment of this program. The following is the abstract from this paper:

"The Boise River Drainage, located in central Idaho, is productive in terms of annual streamflow, a large majority of which is derived from accumulated winter snow pack. There are three dams on the upper river: Anderson Ranch, Arrowrock and Lucky Peak. Capacities of the three reservoirs are: 413,000, 272,000 and 306,000 acre-feet, respectively. Both Anderson Ranch and Lucky Peak have hydroelectric production capabilities. Lucky Peak is located below the first two dams. North American Weather Consultants, Inc. conducted winter cloud seeding programs over the Boise River Drainage above Lucky Peak Reservoir during the water years of 1993-1996. A target/control analysis of these four seasons of seeding indicated an average increase in target area April 1st snow water content of 12% (an average additional 2.50" of snow water content per season).

Additional analyses were performed to estimate the potential economic benefit that might be derived from the seeding program based upon the value of the estimated increased hydro-power production from Lucky Peak Dam. Lucky Peak has an installed turbine capacity of 100mw. It was estimated that a 12% increase in April 1st snow water content would result in an average 16,409 mwh of additional electricity production per year. This amount of additional electricity was estimated to have a value of $820,182. The average annual cost of the cloud seeding program during the four seasons of operations was $85,000. These values result in an average estimated benefit/cost ratio of 9.7/1. This analysis does not consider the value of the additional electricity produced from the Anderson Ranch Dam which is a Bureau of Reclamation facility or the value of the enhanced streamflow to irrigation interests downstream of the Lucky Peak Dam."

1.2.3 Idaho Power

The Upper Payette River drainage in western Idaho has undergone cloud seeding since 2003; a program conducted by Idaho Power. Automated ground-based AgI solution-burning generators and aircraft are employed to conduct the seeding. The program has included some interesting research components, including trace chemistry analyses (Furhman, et al, 2006). Gary Riley, with Idaho Power, provided the following summation of the indicated effectiveness of this program (Table 1-1).

Table 1-1

Indicated Results from the Idaho Power Company's Upper Payette River Winter Cloud Seeding Program

Water Year	Estimated Precipitation Increase %	Estimated Precipitation Increase inches	Estimated Streamflow Increase acre feet	Estimated Additional Power MWH
2003	17	2.4	120,064	60,032
2004	6	1.6	80,042	40,021
2005	7	1.7	85,045	42,523
2006	15	6.4	320,170	160,085
2007	10	2.8	142,140	71,070

1.2.4 Utah Programs

NAWC has been the cloud seeding contractor for a number of Utah winter snowpack augmentation programs covering much of the mountainous terrain in the state since the mid-1970's. Figure 1.2 shows past and current locations of operational seeding programs in Utah, and Figure 1.3 shows the target areas in Utah for the 2007-2008 winter season. These programs employ ground-based AgI solution-burning generators in valley and foothill locations. Numerous mathematical evaluations have been conducted of those programs, some now spanning more than 31 years. The results of the mathematical (non-randomized) estimations of seeding effects averaged over multiple seasons range from 3% to 21% increases, with a gradient of apparent effects increasing from south to north for the program areas located west and on the upwind slopes of the primary north-south oriented Wasatch Range. One of these operational programs was the host of research efforts described in section 4.2.1.2 of this report. For the longest-standing program, positive seasonal results (increases) have been indicated in statistical evaluations of precipitation for 28 of the 29 seeded seasons to date. A plot of the ranked ratios of observed/statistically estimated snowpack for the seeded seasons and the historic base period (non-seeded sample) is shown in Figure 1.4. The dark bars are seeded seasons, and the open bars are the historical base period years.

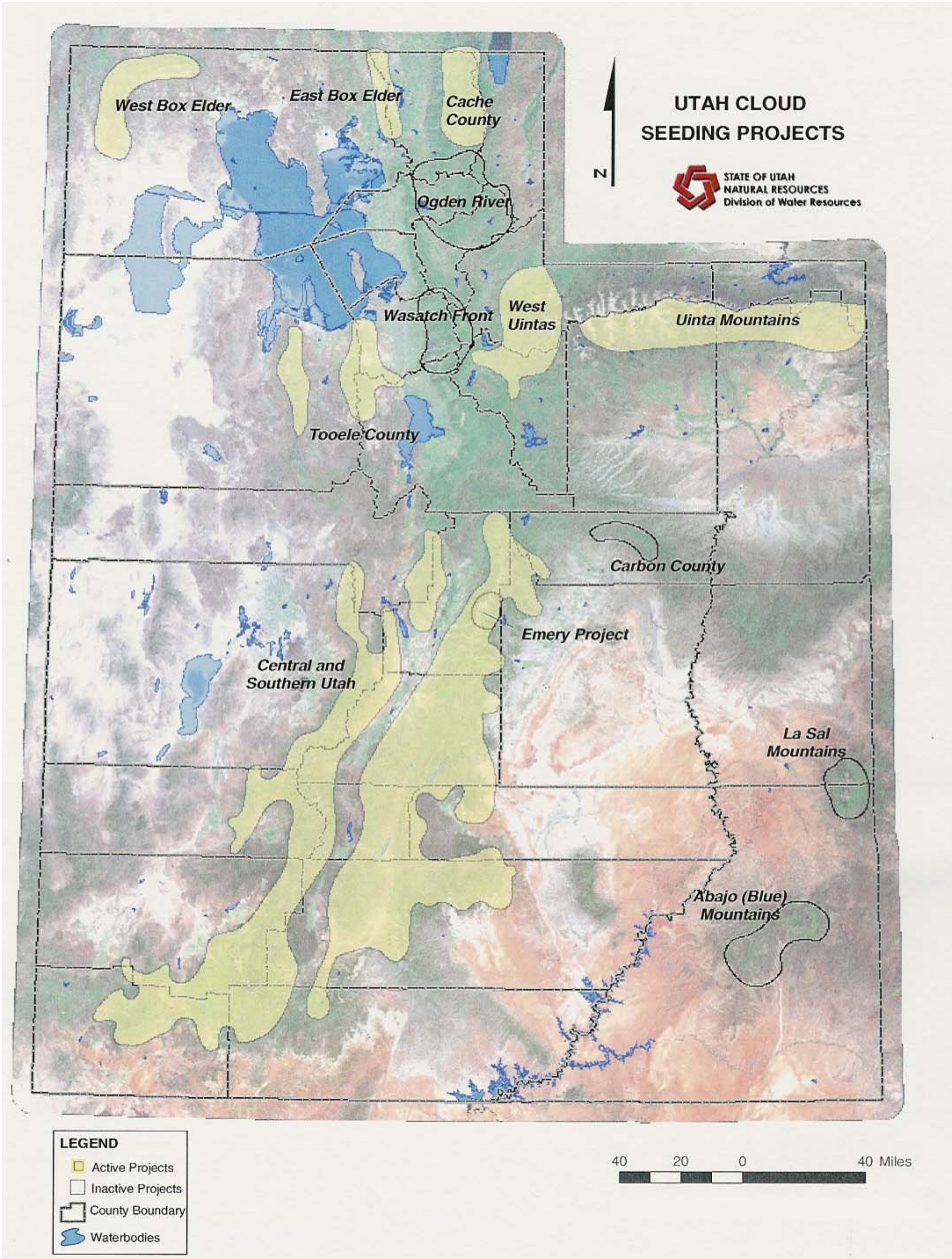

Figure 1.2 Past and Current Operational Cloud Seeding Programs in Utah

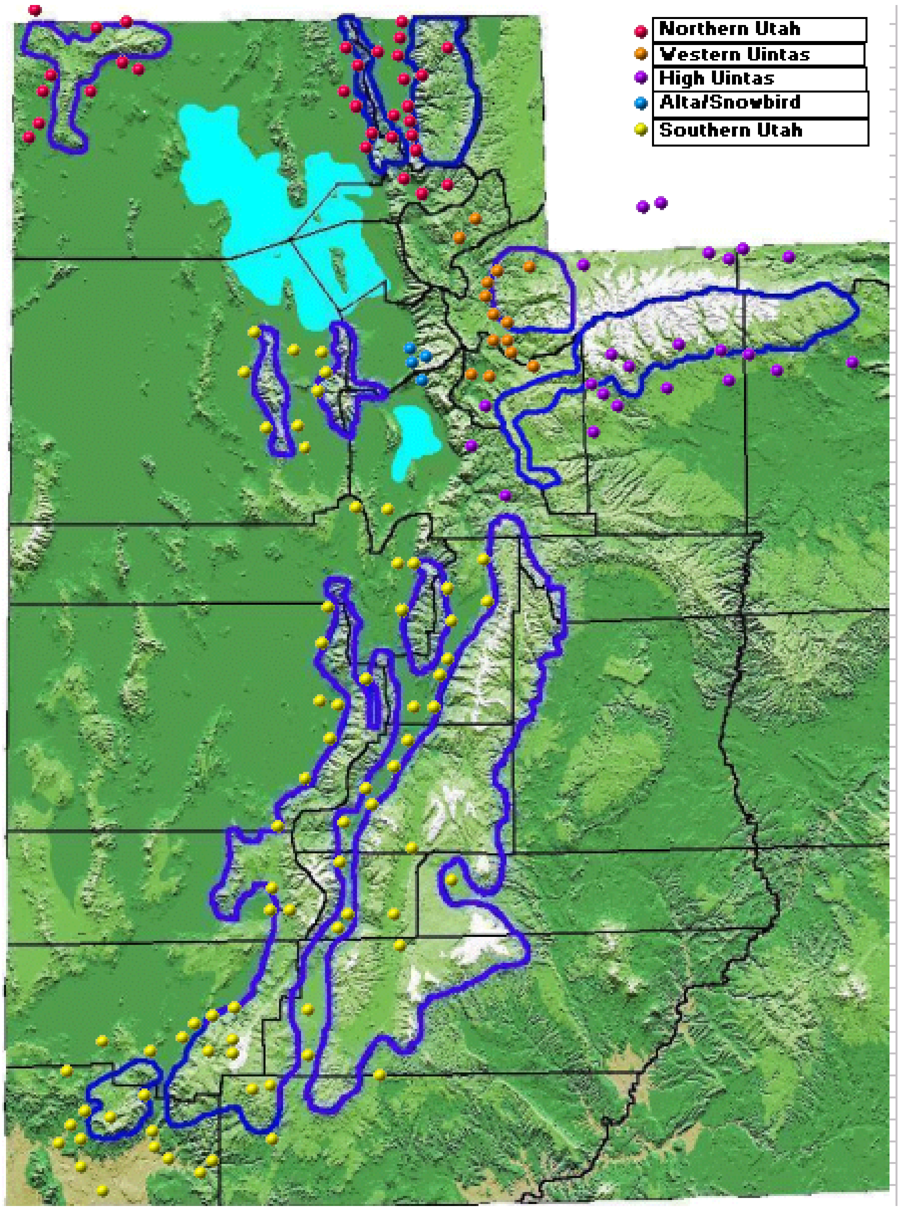

Figure 1.3 Locations of Cloud Seeding Target Areas and Ground Generator Sites within Utah, 2007-2008 Winter Season

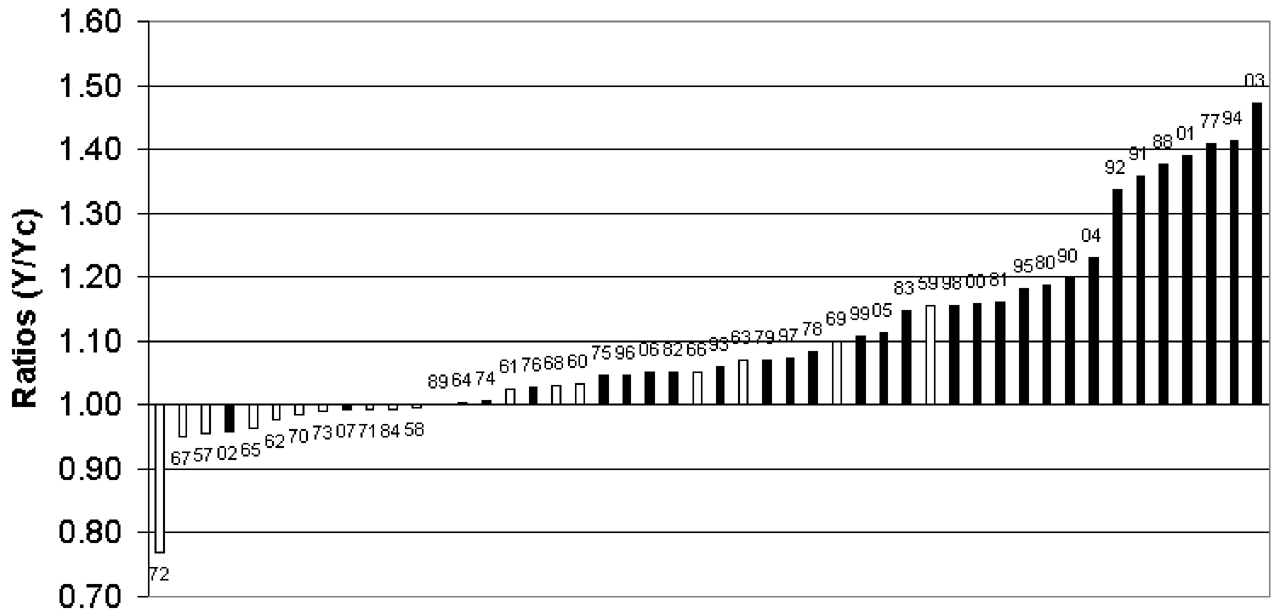

Figure 1.4 Southern Utah Seeded Year Target/Control Ratios through 2007

Effectiveness estimations for each of the Utah operational programs are shown below. All estimations are based on NAWC's standardized non-randomized target/control regression method, analyzing precipitation and snowpack data.

- Northern Utah (Cache and eastern Box Elder Counties)

Precipitation: 17% average seasonal increase; 16 of 19 seasons positive.

Snowpack: 10% average seasonal increase; 16 of 19 seasons positive.

- Northern Utah (northwestern Box Elder County)

  Precipitation: no sites available for analysis.
  Snowpack: 17% average seasonal increase; 13 of 15 seasons positive.

- Eastern Tooele County

  Precipitation: 21% average seasonal increase; 22 of 23 seasons positive.
  Snowpack: 16% average seasonal increase; 18 of 22 seasons positive.

- Western Uinta Mountains (Weber and Provo Rivers)

  Precipitation: 5% average seasonal increase; 8 of 13 seasons positive.
  Snowpack: 5% average seasonal increase; 10 of 12 seasons positive.

- High Uinta Mountains (southern slope)

  Precipitation: 3% average seasonal increase; 3 of 5 seasons positive.
  Snowpack: 3% average seasonal increase; 2 of 3 seasons positive.

- Central and Southern Mountains

  Precipitation: 14% average seasonal increase; 28 of 29 seasons positive.
  Snowpack: 4% average seasonal increase; 20 of 29 seasons positive (note, NAWC's annual program report for the 2003-2004 winter season indicated that a change (reduction) in indicated results was due to our decision to use NRCS adjusted snow water contents in this evaluation. The precipitation evaluations are considered more representative for this target area).

A recent summary of the Utah cloud seeding programs was published in the WMA Journal of Weather Modification (Griffith, et al, 2009).

1.2.5 Nevada/Desert Research Institute Programs

The State of Nevada, through the Desert Research Institute (DRI) has conducted operational cloud seeding since the 1960's, beginning in the Tahoe area and expanding to other areas in more recent decades. These programs are an outgrowth of DRI weather modification research programs funded through the U.S. Bureau of Reclamation and the National Oceanic and Atmospheric Administration (NOAA). Most relevant to the ESRBP are the programs for the Ruby and Tuscarora Mountains in northeastern Nevada and the Toiyabe Mountains in the central portion of the state. The programs employ automated ground-based AgI solution-burning generators and have been in operation since the 1980's.

The following is quoted from a DRI web site:

"Benefits vary with the seasonal frequency of suitable weather opportunities. Research results have documented precipitation rate increases of 0.1 - 1.5 millimeters per hour due to ground-based seeding during the proper weather conditions. Estimates of augmented water from seeding have varied from 20,000 to 80,000 acre-feet over each of the last ten years. Seasonal percentage increase estimates have varied from four to 10%; generally greater in drought years; less in above normal years. The cost of augmented water, based on the cost of the program, has ranged from $7 to about $18 per acre-foot."

1.2.6 Eden Valley

The WMI Weather Modification Study (WMI, 2005) contains a description of a long-term program conducted by the Eden Valley Irrigation District headquartered in Farson, Wyoming. The following is a description of this program contained in the referenced report:

"The Eden Valley Irrigation District is the only entity presently actively seeding clouds on an annual basis. Each winter, from 15 November through 30 April, the EVID uses three ground-based cloud seeding ice nuclei generators to seed clouds upwind of the southern Wind River Mountains. These generators are placed at 10 mile intervals along U.S. Highway 191 north of Farson. These generators which burn a silver iodide solution are complimented by two additional high-altitude propane ice crystal generators. While the generators along Highway 191 are operated manually by EVID staff, the propane generators are remote controlled and operated by the Provo, Utah office of the Bureau of Reclamation.

The EVID program was designed by the University of Wyoming's Department of Atmospheric Sciences, and for a time, also operated by the Department. However, the program is presently operated independently by the EVID, and the Wyoming State Engineer's office issues the operations permit to the irrigation district itself.

Operations have been conducted annually since 1975. The irrigation district believes it realizes an 11% to 13% increase in snowfall (water equivalent) as a result of the seeding operations."

1.3 Summary of Findings from Relevant Research and Operational Winter Cloud Seeding Programs

Key Indications

From a review of the relevant research and the large and quite consistently positive overall results of (albeit largely non-randomized) statistical estimations of the effectiveness of operational programs, the following key points emerge:

- It appears that the potential exists for winter snowpack augmentation in the mountainous west. The potential effects range from about 5% to about 15%.
- It is clear that statistically significant evaluations of seeding effects are exceedingly difficult to achieve, due to the relative magnitude of natural precipitation variability compared with the magnitude of anticipated cloud seeding effects. Carefully controlled, randomized experiments are considered necessary by some for attaining such results.
- The basic prerequisite ingredient for cloud seeding potential is the presence of supercooled liquid water (SLW), which has been observed to develop at low altitudes over the windward slopes of mountain ranges. The SLW develops during a sufficiently large proportion of the time during winter storms to constitute a credible target for cloud seeding efforts. This critical characteristic has been identified not only in the programs cited in this report, but also in numerous programs and investigations in a wide variety of locations around the world.
- A key challenge is to identify the most effective methods necessary to "tap" the SLW reservoir, such that the affected precipitation will fall to the surface within the intended area of effect.

- Critical factors regarding effective seeding methods and materials include atmospheric stability, the temperature thresholds of various seeding materials, times/distances available for growth of the seeding-induced ice particles, etc.
- AgI solution formulations incorporating sodium iodide and para-dichlorobenzene, acting more quickly via the condensation-freezing nucleation method, are available for operational use.
- Each potential cloud seeding method has benefits and limitations. A number of program-specific considerations must be factored into selection of the most appropriate seeding method(s). More than one seeding method may well be appropriate for a given program area.
- A practical approach to seeding method selection is appropriate, weighing the potential benefits each may achieve against the costs and the logistical considerations associated with each prospective method. In other words, is a given seeding method worth the effort? What is each seeding method's relative (incremental) contribution (value) versus its cost? This is a basic benefit/cost issue of the type common to every day decision-making in business, etc.

Siting of ground-based AgI generators should take into account the trapping effects of surface-based temperature inversions. The character and frequency of such inversions in the region **during seedable storm occurrences** should be determined via analysis of regional observations. **Occurrences of trapping temperature inversions during non-seedable storm periods or non-stormy periods are generally irrelevant and must not be included in such climatologies.** Modeling (using only validated model results) can be helpful in such considerations, but analysis of real data is much preferred, especially if a suitable period of record is available. The typical (range of) height of the top of the inverted layers can be used to establish a critical elevation for ground-based generators if the inversion frequency of occurrence during seedable storm occurrences is deemed significant. In any case, the critical elevation should be kept in mind during the site selection process. The frequency of occurrence issue can be used to assess the apparent seasonal benefit/cost of using lower elevation generators, given their seeding coverage advantages. The seeding formulation issue should also be addressed, with close attention to activation temperature threshold and the speed of activation of the nuclei produced.

Siting of high elevation generators (AgI or propane) should take into account the attendant constraints pertaining to their cost effectiveness. These are primarily distance-to-target issues, i.e., considerations of adequate time for the seeding-induced ice particles to grow and fall out into the intended area of effect. In the case of propane, the generators must be at sufficiently high elevations to consistently position them in-cloud to have any effect. In the case of AgI, their location in-cloud adds the potential benefit of forced condensation-freezing. The assessment issues include the precipitation rates possible, the degree of plume spread and, thus, the crosswind spacing required to produce overlapping plumes sufficiently far upwind to produce a cost effective benefit. High elevation sites typically are located strategically in areas with difficult access, necessitating the significant additional cost of high capacity, full automation, communications equipment and on-site solar power (panel) system. Obtaining site permission/leases can also be problematic. Storm-to-storm equipment reliability can be difficult to ascertain with automated systems due to less frequent on-site human involvement. The costs of repair and replenishment visits add to the benefit/cost consideration.

Use of aircraft for operational seeding, albeit costly, does offer some benefits over ground-based releases. Those include better targeting of the low altitude SLW layer above 500-1000 m AGL when safety considerations allow, seeding of SLW layers when low elevation stable layers or temperature inversions would likely trap ground-based releases from lower or even upper elevations, and seeding when the nucleation temperature threshold is significantly above a mountain barrier summit height.

1.4 Relevant Feasibility Studies

There have been two recent weather modification feasibility/ design studies conducted in Wyoming. The Wyoming Water Development Commission headquartered in Laramie, Wyoming funded these studies. Weather Modification, Inc. of Fargo, North Dakota, conducted the first study. North American Weather Consultants conducted the second study. A third publication, a White paper prepared by North American Weather Consultants, also has some relevance to this ESRBP study.

1.4.1 Medicine Bow, Sierra Madre and Wind River Study

The Wyoming Water Development Commission awarded a contract to conduct a Level II weather modification feasibility study through a competitive bid process to Weather Modification, Inc. (WMI) in June 2004. The Research Application Laboratory under the National Center for Atmospheric Research located in Boulder, Colorado served as a sub-contractor to WMI to conduct atmospheric modeling work. The proposed target areas were comprised of two different mountainous areas; the Wind River Range located in west-central Wyoming and the Medicine Bow/Sierra Madre Ranges located in south-central Wyoming.

This WMI study concluded that a pilot program could be effectively conducted in the proposed target areas. Quoting from the WMI final report (WMI, 2005):

" This pilot program, as defined, would be conducted for five winter seasons and would treat clouds with silver iodide based seeding agent to increase snowpack in the Wind River and Medicine Bow-Sierra Madre Ranges. Seeding would be conducted with ground-based and airborne facilities. It is estimated that snowpack would be increased by a minimum of ten percent, and quite possibly twenty percent, based on the findings from other recent programs whose evaluations have been published in the reviewed scientific literature.

Evaluation would be double-faceted: effects upon precipitation would be assessed, and physical measurements of cloud processes within both natural and seeded clouds would be made. Advanced numerical (computer) modeling would be included to *select optimum seeding sites, predict which seeding facilities should be used in each storm, and to enable detailed analysis of program effects.*

Total Programed cost for the five-year program is $8.825 million, for an annual cost of $1.765 million. Conservative estimates of programed benefits range from a minimum of 223,000 to 446,000 acre-feet per season. Cost per acre-foot is estimated to be a maximum of $7.91, to a minimum of $3.96 per acre-foot. The value of the additional water thus generated is conservatively estimated to range from $4.2 million to $8.3 million per season, however these estimates do not include any benefits that might be realized through increased hydro-electric power generation, improved recreation and fisheries, tourism, slowing the melting of glaciers, improved water quality and conditions for certain endangered species, or by meeting downstream water requirements.

Value of the additional water generated is estimated to range from $10-$12 per acre-foot for agricultural areas, and from $75-$100 per acre-foot for municipal and industrial uses. However, water demand, and thus values are constantly increasing. According to Ed Harvey, Inc., an economic consulting firm that has contributed significantly to Wyoming river basin planning, the City of Ft. Collins is presently paying $400 per acre-foot for water rights to satisfy its municipal demands, and in some industrial applications the value is known to be up to $5,000 per acre-foot. The above mentioned estimates reflect only the current, conservative values, however."

The results from WMI's final report were presented to the Wyoming legislature. The Wyoming legislature approved the proposed five-year pilot program in the fall of 2005. Request for proposals for two different contractors to perform the operations, final design, modeling and evaluation phases of the program were released. WMI was selected to perform the operations and the National Center for Atmospheric Research, located in Boulder, Colorado, was selected to perform the design, modeling and evaluation phases of the program. Limited activities began in the latter part of the 2005-2006 winter season. Activities on this program have continued to the present time. No preliminary results from this program have been published. Final results will not be available until after completion of the five-year field experimentation.

1.4.2 Salt River and Wyoming Ranges Study

In January 2005 the Wyoming Water Development Commission released a Request for Proposals (RFP) for the conduct of a Level II weather Modification Feasibility study. The area of interest was the Salt River and Wyoming Ranges located in western Wyoming. NAWC responded to this RFP and was ultimately awarded the contract in June 2005. NAWC completed a final report on the study in December 2006 (Griffith et al, 2006). Some of the findings include:

The feasibility/design study has determined that an effective winter cloud seeding program can be established and operated for the Salt River and Wyoming Ranges. The program has the potential to enhance the snowpack by ~10% during an average winter season, with the resultant additional annual runoff estimated to be about 109,573 acre feet utilizing the combination of three different seeding methods. Conduct of a proposed single winter season of area-specific meteorological monitoring prior to the start of operational seeding would serve to refine the preliminary program design.

A preliminary seeding program design was developed. Some of the key elements of the proposed design are as follows:

- The suggested target area includes elevations above 8,000 feet located in Lincoln and Sublette Counties.
- A "core program" is proposed, utilizing ground-based manually operated silver iodide generators. This "core program" could be augmented through the addition of remotely controlled ground generator and/or aircraft seeding modes.
- Supplemental mid-high elevation remotely controlled silver iodide generators are recommended for consideration, subject to benefit/cost considerations.
- Fast-acting silver iodide seeding solution formulations are recommended.
- Airborne seeding may be considered, subject to benefit/cost considerations.
- Seeding operations should be conducted full-time, with no randomization.
- Seeding suspension criteria will be followed with primary emphasis on percent of normal snowpack values and avalanche conditions.
- The primary seeding season will be November through March, with possible extension into April.
- Radar data from the National Weather Service radars can be used to view storms approaching the program area; a program-specific radar is not considered necessary.
- A one-season campaign of rawinsonde, radiometer and ice detector measurements are recommended. Analysis of the one-season specialty measurements, in conjunction with other routinely available meteorological information, will assist in completion of the final program design.
- Surface snow chemistry sampling and analyses should be used to verify seeding material targeting.
- Historical target and control regression methods should be used to estimate seeding effectiveness.

A peer reviewed paper was prepared that summarized this study (Griffith, et al, 2007).

1.4.3 <u>Upper Colorado River Commission White Paper</u>

NAWC prepared a White paper in 2006 entitled "The Potential Use of Winter Cloud Seeding Programs to Augment the Flow of the Colorado River" (Griffith and Solak, 2006). The Executive Summary from this paper is reproduced in the following:

"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 operational 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 programions 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 programs.*

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 programs 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."*

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APPENDIX B

ENVIRONMENTAL AND LEGAL ASPECTS

1.0 REVIEW OF ENVIRONMENTAL AND LEGAL ASPECTS

1.1 Environmental Considerations

There are a number of issues related to the conduct of a cloud seeding program that are concerned with perceived or potential negative impacts from the seeding program on the environment or on residents in and downwind of the region of the cloud seeding operations area. A summary of what is known regarding the items of particular concern is provided in the following.

1.1.1 Downwind Effects

Perhaps the most frequently asked question regarding the possible establishment of a cloud seeding program in an area that has not previously been involved in 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 perhaps surprising answer to this question is “no.” This answer is based upon analysis of precipitation in a number of 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 wintertime programs was one conducted by Colorado State University scientists in the Climax, Colorado area. That area is located in a mountainous region in the Central Colorado Rockies. The 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 programs. 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 in 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 makes 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. That 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 program 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 program's target area. Target area analyses of December-March high elevation precipitation data for this program indicate an overall seasonal increase of about 14%. Estimations of downwind effects are made for distance bands downwind as far as 150 miles. The downwind analyses indicate increases of similar magnitude to those for the target, expressed as percentages or ratio values, extending to about 100 miles downwind. Beyond 100 miles the ratio values decay, reaching about 1.0 (e.g., no effect) at about 125 miles. Expressed as average-depth precipitation amounts, the target area precipitation difference is about 1.4 inches of additional water, while the values within downwind distance bands range from 0.4 to 0.25 inches, reaching zero at about 125 miles."

1.1.2 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 presented 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 the Metropolitan Water District of Southern California (Ryan, 2005) 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 programs, many of which have been in operation for 30 to 40 years (WMA, 1996)".

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

Also worth noting here is a statement by the Weather Modification Association in its formal policy statement (WMA 2005):

> *"The potential environmental impacts of cloud seeding have been addressed in many studies. No significant adverse environmental impacts have been found due to use of silver iodide, the most commonly used seeding material, even in program areas where seeding has been conducted for fifty years or more".*

Specific to silver concentrations in snowmelt water, Marler (2007) reported on lake water and sediment studies conducted for two long-term seeding programs operated by the Pacific Gas and Electric Company (PG&E) in the Sierra Nevada of California. Samples from a number of surface sites were analyzed for their silver content. The program areas are subject to moderate seeding material releases over periods of nearly fifty years, with annual amounts varying from 9-90 pounds for the Mokelumne area and from 45-180 pounds for the Lake Almanor area.

The report presented the following characteristics regarding silver iodide and silver chloro-iodide compounds used in cloud seeding.

- *"Have extremely low solubility in water*
- *Remain solid particles in air, cloud, precipitation*
- *Do not ionize to produce Ag+ under ambient environmental conditions*
- *Are not very bio-available in the environment*
- *Background Ag concentrations in Sierra snow < 2.0 ppt(ppt= gAg/ml x 10-12)*
- *[Ag] in seeded snow typically range 40–60 ppt in layers sandwiched between unseeded snow.*
- *Total snowpack profile mean Ag concentrations average 5-20 ppt in highly effective seeding programs"*

Conclusions from the overall study include the following (from Marler, 2007)

- *"High resolution analysis of water, sediment and biological samples from areas subjected to long-term, 50 year+, cloud seeding programs, specifically PG&E's Mokelumne and Lake Almanor cloud seeding programs, support the following:*
- *The amount of silver iodide released to the atmosphere in cloud seeding is small, and even after many years of cloud seeding operations the resulting environmental concentrations very small to non-detectable.*
- *Given the stability of silver iodide compounds, extreme insolubility of silver iodide in water and the absorptions of ionic silver by colloids found in the sediments and aquatic vegetation, silver concentrations in the Mokelumne and Lake AlmanorBasin from cloud seeding are expected to be minimal.*
- *Since the monitored levels are low, usually below the detection limit in the target watershed, it is unlikely that continued cloud seeding operations would result in any significant increase in silver concentrations in the target watersheds.*
- *Silver concentrations were below regulatory standards. Therefore, continued operations should not result in any significant chronic effect to sensitive aquatic organisms.*
- *There is little to suggest the silver from cloud seeding gets into the system and bio-accumulates in organisms."*

1.1.3 Avalanche Considerations

Avalanche hazard is a factor worthy of consideration due to the amount of backcountry recreational activity in the program area. Contact with the USDA Forest Service in the region of the program area yielded a referral to the avalanche information and advisories issued via the *Backcountry Avalanche Hazard & Weather Forecast* produced from Jackson Hole, Wyoming, in cooperation with the Bridger-Teton National Forest. Two districts covered in those advisories, the Greys River and Teton Districts, abut the eastern boundary of the eastern portion of the seeding program area. Additional information for the near region is available from the Gallatin National Forest Avalanche Center, which operates from Bozeman, Montana. Their forecast and advisory area abuts the seeding program area on the north, including the West Yellowstone-Targhee Pass-Lionhead Mountain region. Monitoring of these sources could provide an index of general conditions in the highest elevation backcountry portions of the seeding program area. An additional potential source is the Sawtooth National Forest Avalanche Center in Ketchum, Idaho. That group is focused on avalanche conditions for the central mountains of Idaho, but apparently may occasionally issue a statement for the program area. However, this would not be considered a primary source.

Conditions are assessed daily during the winter months and reported to the named central locations from which daily advisories are issued. The information is readily available via the internet in the form of a *Backcountry Avalanche Hazard & Weather Forecast* which can be accessed at www.jhavalanche.org from the Jackson Hole source and the *Gallatin National Forest Avalanche Advisory* from Montana at www.mtavalanche.com. The Sawtooth National Forest Avalanche Center website can be viewed via www.avalanche.org.

The daily products typically consist of a weather summary for the preceding 24-hr period, mountain weather forecasts for the current day (and in some cases, three days), and a General Avalanche Advisory. That advisory includes an avalanche hazard rating within the widely-accepted national standard range of five levels of hazard. During the latter portion of the winter season, when more spring-like conditions can occur, separate hazard ratings may be shown for morning and afternoon. The five national hazard categories and their published definitions are shown here.

Low:	Mostly stable snow exists. Avalanches are unlikely except in isolated pockets.
Moderate:	Areas of unstable snow exist. Human triggered avalanches are possible. Larger triggers may be necessary as the snowpack becomes more stable. Use caution.
Considerable:	Dangerous unstable slabs exist on steep terrain on certain aspects. Human triggered avalanches probable. Natural avalanches possible.
High:	Mostly unstable snow exists on a variety of aspects and slope angles. Natural avalanches are likely. Travel in avalanche terrain is not recommended.
Extreme:	Widespread areas of unstable snow exist and avalanches are certain on some slopes. Backcountry travel should be avoided.

The Jackson Hole web site includes archives of the daily advisories for a period of the most recent one or two years. Daily data from the archive for two winter seasons were tabulated for the Greys River District (east of the program area), noting the highest hazard category shown for each of 312 total days. The seasonal occurrence and average proportion of days within each category are shown in Table 1-1, providing a snapshot of the magnitude and hazard level in a neighboring region.

Table 1-1
Avalanche Advisories for the 2001-2002 and 2002-2003 Winter Seasons
Greys River District (western Wyoming)

Hazard Cat.	2001-2002	2002-2003	Total	Percentage
Extreme	0	0	0	0%
High	10	14	24	8%
Considerable	45	58	103	33%
Moderate	67	60	127	40%

Low	28	30	58	19%

The information contained in the daily advisories appears to be adequately objective and consistently provided to be of use in suspension considerations in the ESRBP program. From the language in the category definitions, it would seem that days rated as in the Extreme or High categories should trigger a temporary seeding suspension. Further discussion with the program sponsors will determine how the avalanche information should best be incorporated into operational decision-making.

1.1.4 Snow Removal

Some have questioned what the associated costs are related to the removal of snow that is created by winter cloud seeding programs. This topic was addressed in a couple of studies. One such study was performed by the Colorado Department of Natural Resources (Sherretz and Loehr, 1983). The conclusions from this study are as follows:

> *"Simulating the effects of cloud seeding on the costs of snow removal indicates that the costs do increase when recorded snow amounts, in approximately one-third of the storms in selected winters, are augmented by 25 percent. The increases in costs range from 0.8 percent to 12.6 percent in the counties studied. Average increases are 6.1 percent in winters of high and average snowfall, and 4.9 percent in winters of low snowfall. Costs in winters of low snowfall average 81 percent of costs in winters of average snowfall, while costs in winters of high snowfall average 141 percent of costs in winters of average snowfall. These variations of 19 percent and 41 percent indicate that costs generally change more with natural variations in seasonal snowfall than with augmentation.*
>
> *Actual effects of cloud seeding on the costs of removing snow cannot be determined definitively, however, until more accurate records of employee and equipment expenses are available and until atmospheric scientists determine if, and by how much, seeding can increase snowfall. Recommendations for record-keeping include daily accounting of the hours employees spend performing removal tasks, hours machines are used, maintenance costs and fuel consumption."*

The Bureau of Reclamation supported contractors that designed and conducted a winter cloud seeding research program in the American River Basin of the northern Sierra Nevada Mountains of California. This program was known as the Sierra Cooperative Pilot Program (SCPP). The SCPP preliminary studies included assessments of the effect of the program upon highway use, safety, and operation and maintenance costs.

A California Department of Transportation (CALTRANS) memorandum report (CALTRANS, 1976) discussed socio-environmental effects that might occur. The study considered:

1) The effect if accumulated snowpack were increased up to 15 percent per annum in normal or below-normal years
2) Manpower and equipment requirements for snow removal per year and per storm under historical conditions
3) The costs for dry, average, and wet years

The report noted that avalanche control has been required only on Route 50 in El Dorado County between Echo Summit and Meyers. No substantive correlation was found between an incremental storm increase and the cost of highway avalanche control.

The study found little direct relationship to increased costs for small incremental changes in storm size because of the amount of equipment and manpower necessary to maintain a traversable roadway under frost conditions or handle the problems of freeze-thaw of snowbanks adjacent to the roadway which cause icy conditions. Also, road closures are more frequently caused by blowing and drifting snow or severe icing conditions rather than the amount of snowfall.

Existing recorded data do not allow an analysis of costs involved in snow removal for small incremental increases in precipitation. However, data are available for maintenance costs related to storm severity.

1.1.5 Delay of Snowmelt

One concern formerly mentioned in conjunction with cloud seeding programs in the west was: Would the increases in snow due to cloud seeding extend the snow melt period? This concern was voiced by ranchers having grazing rights in some of the targeted areas who wondered if the cloud seeding would delay their moving of livestock into these areas in the springtime. This topic was addressed in an environmental study conducted in the Uinta Mountains of Utah, which was funded by the Bureau of Reclamation offices in Denver (Harper, 1981). The conclusion reached in this study was that "An increase of 10% in the average snowpack is estimated to retard the 75% snow-free date 0.7 – 1.5 days." In other words, this should not be a significant concern.

1.1.6 General Statements on the Potential Environmental Impacts of Winter Cloud Seeding

A large number of studies have been conducted in the western United States related to the potential environmental impacts of winter cloud seeding. Most of these studies were funded under the Bureau of Reclamation's "Skywater Program". Four programs of note concerned with wintertime programs were:

- 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 Program. 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, the findings from these studies were that significant environmental effects due to the possible conduct of cloud seeding programs in these areas were not expected to occur. A couple of examples that support this conclusion are as follows: A statement made in the final report on the San Juan Mountains program (Steinhoff and Ives, 1976): “The results of the San Juan Ecology Program 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 study’s 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.”

The Bureau of Reclamation published an “Environmental Assessment and Finding of No Significant Impact (Harris, 1981) for the Sierra Cooperative Pilot Program. Quoting from the introduction of this report:

“*This document and the program environmental assessment serve as the basis for determination that no further action is necessary to comply with the National Environmental Policy Act of 1969 (Public Law 91-190) for the following reasons:*

1) The Sierra Cooperative Pilot Program Environmental Assessment examines a research program designed to seed, on a randomized basis, some of the cloud types which occur within winter storms in the Sierra Nevada of California and Nevada. The increase in annual precipitation expected from seeding all eligible storms during an average or less-than-average year would be 10 to 15 percent. The annual precipitation increase expected from randomized seeding of selected cloud types would be 5 to 7.5 percent. The report analyzes the potential effect of these increases upon weather elements, hydrologic and physiographic phenomena, plant and animal communities, the human environment, and land and water resource use in the program area. It also discusses possible impacts of the seeding agents, dry ice and silver iodide. The report concludes the research program will not result in significant or adverse effects upon the environment.

2) *Consultation with Federal and State agencies has resulted in the determination that this program will not affect endangered or threatened species of plants or wildlife or their habitats in a significant or adverse manner.*
3) *Archeological and historic sites and sites of extraordinary aesthetic value will not be significantly or adversely affected by the program.*
4) *Program activities and resultant increases in precipitation will not affect the human environment, lifestyle, or existing land and water resource use in a significant or adverse manner. The program design includes suspension criteria to prevent operations during periods that would lead to public safety hazards."*

The American Society of Civil Engineers has published its Manual 81 on Engineering Practice, entitled *Guidelines for Cloud Seeding to Augment Precipitation* (ASCE 2006). A section of that publication addresses environmental issues relating to weather modification. A key summary paragraph from Manual 81 is shown here.

"The essence of the results is that changes that might be expected in the environmental factors (1) were most often subtle, nil, or indiscernible in relation to other natural influences (e.g., effects of fire or insects on forest vegetation); (2) would be of the same type and magnitude as would result from a sustained increase of a corresponding percent(age) in natural precipitation (e.g., as a gradual change in herb species composition might occur in a wetter climate); (3) might be beneficial as often as not and depending on point of view (e.g., as when fish habitat increases with lake level); and (4) would have net outcomes that strongly affect ecosystem management practices (e.g., as when increased weed growth and grassland productivity occur together). During the 1970's, seeding agents, chemical complexes of silver iodide, were examined for ecological effects (Cooper and Jolly, 1970; Klein, 1978). Conclusions from those studies point to little or no effects on terrestrial or aquatic biological communities, either immediately or after many, many years of silver iodide application in the small dosages possible from cloud seeding (Reinking et al. 1995)."

1.2 General Legal Implications

There are legal implications associated with the conduct of cloud seeding programs. For example, who owns any additional water produced from cloud seeding activities? Most state regulations claim ownership of these waters remains with the state to be distributed according to the existing water rights in the area. There are permitting and reporting requirements normally associated with the performance of cloud seeding programs. There would be both state and national requirements associated with the ESRBP program. These requirements are summarized in Section 1.3.

Another possible legal consideration is the level of exposure the program sponsors may have regarding legal responsibility for any perceived damages caused by the seeding activities? For example, if seeding was conducted and a flood occurred in or near the program's target area, would the sponsors be held liable? Such situations are sometimes referred to as the possible "consequential effects" of cloud seeding. The first line of defense in such circumstances is to have adequate safeguards built into the design of the seeding program to suspend seeding operations if/when questionable circumstances develop. A few lawsuits have been filed over the years, claiming damages caused by cloud seeding programs. According to ASCE Manual No. 81 (1995): "Defendants have won almost all liability suits." The primary reason for this outcome is that the burden of proof falls upon the plaintiffs to prove that the cloud seeding activities caused or contributed to the damages.

Some weather modification operators also carry a special type of insurance commonly known as "consequential effects of cloud seeding liability insurance." This insurance protects both the operator and sponsors of insured programs.

Another type of legal requirement is program permitting and reporting requirements. There will be some permitting and reporting requirements associated with the conduct of a cloud seeding program should the decision be made to proceed to an operational phase based upon this preliminary design work.

1.3 Permit and Reporting Requirements

1.3.1 State of Idaho Permit Requirements

The State of Idaho has a statute that requires the registration of producers of artificial rainfall. The reference is Title 22, Chapter 32, Rainfall- Artificial Production, Section 22-3201 (registration) and 22-3202 (log of activities).

Section 22-3201 states that "Any person, persons, association, firm, or corporation conducting or intending to conduct within the state of Idaho operations to assist artificially in production of or to produce artificially rainfall shall register with the department of agriculture of the state of Idaho. Such registration shall require the filing of the name of the person, association, or corporation, its residence, or principal place of business in the state of Idaho and the general nature of the business to be conducted."

Section 22-3202 states that "Such person, persons, association, firm or corporation shall thereafter file with the said department of agriculture a log of all its activities in the production, artificially, within this state, of rainfall."

NAWC has been granted a number of annual permits following the procedures established by the Idaho Department of Agriculture.

1.3.2 U.S. Forest Service and Bureau of Land Management Permits

Permits are normally required to install any type of equipment on U.S. Forest Service or BLM lands. Since we are tentatively recommending that remotely controlled silver iodide generators be considered in the conduct of the ESRBP, special use permits may be required. Similar permits would be required for either Forest Service or BLM lands. There would likely also be some permit or approval process when siting equipment on Indian Tribal Lands.

1.3.3 National Oceanic and Atmospheric Administration Reporting

In 1971, Public Law 92-205 was enacted that required all non-federally sponsored attempts to modify the weather be reported to the Secretary of Commerce of the United States. Public Law 92-205 requires the submittal of Initial, Interim and Final reports covering weather modification activities for individual target areas. An initial report is required each year seeding is planned and at least 10 days prior to the start of activity. Interim reports are required for those programs active on January 1st of each year and must be filed within 45 days of that date. A Final report must be submitted within 45 days after the completion of the weather modification activity (Golden, 1995). The information required in the interim activity and final reports include: 1) number of weather modification days each month, 2) number of modification days for purposes of increasing rain or snow, reduction of hail, fog or other, 3) hours of apparatus operation (airborne or ground), and 4) type and amount of cloud seeding agent used.

It is important to note that Public Law 92-205 is a reporting requirement but establishes no regulatory authority.

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APPENDIX C

BOISE RIVER OPERATIONAL PROGRAM SEEDING EVALUATION RESULTS TABLES

Precipitation - original set, December - March

Regression (non-seeded) period:					
Year	XOBS	YOBS	YCALC	RATIO	EXCESS
1968	14.68	15.34	16.66	0.92	-1.32
1969	21.64	27.21	25.36	1.07	1.86
1970	21.98	25.26	25.78	0.98	-0.52
1971	21.07	24.45	24.65	0.99	-0.20
1972	21.69	24.07	25.42	0.95	-1.35
1973	14.88	16.82	16.91	0.99	-0.09
1974	20.66	23.52	24.14	0.97	-0.62
1975	20.76	22.90	24.27	0.94	-1.36
1976	15.92	17.50	18.22	0.96	-0.72
1977	8.01	7.31	8.33	0.88	-1.02
1978	20.34	23.16	23.74	0.98	-0.57
1979	13.54	14.95	15.24	0.98	-0.29
1980	17.51	20.63	20.20	1.02	0.43
1981	16.06	17.70	18.39	0.96	-0.69
1982	23.85	28.49	28.13	1.01	0.37
1983	21.91	27.68	25.70	1.08	1.97
1984	16.45	18.43	18.88	0.98	-0.45
1985	10.69	11.62	11.68	1.00	-0.06
1986	20.24	24.39	23.62	1.03	0.78
1987	9.66	10.90	10.39	1.05	0.51
1988	13.64	16.60	15.36	1.08	1.24
1989	15.90	18.07	18.19	0.99	-0.12
1990	11.55	12.73	12.75	1.00	-0.02
1991	10.50	12.91	11.44	1.13	1.47
1992	8.51	8.66	8.95	0.97	-0.29
1998	15.73	17.97	17.98	1.00	-0.01
1999	20.06	23.21	23.38	0.99	-0.17
2000	16.68	19.89	19.17	1.04	0.72
2001	7.97	8.77	8.28	1.06	0.49
Mean	16.28	18.66	18.66	1.00	
Seeded period:					
Year	XOBS	YOBS	YCALC	RATIO	EXCESS
1993	18.62	22.17	21.58	**1.03**	**0.58**
1994	10.83	13.41	11.86	**1.13**	**1.55**
1995	19.47	24.34	22.65	**1.07**	**1.69**
1996	21.85	25.34	25.62	**0.99**	**-0.28**
1997*	24.68	32.14	29.16	**1.10**	**2.99**
2002	15.02	18.15	17.08	**1.06**	**1.06**
2003**	19.69	21.26	22.92	**0.93**	**-1.65**
2004**	15.06	18.44	17.14	**1.08**	**1.30**
2005**	10.44	13.28	11.36	**1.17**	**1.92**
2008**	16.70	21.57	19.19	**1.12**	**2.38**

2009**	15.00	19.71	17.07	**1.15**	**2.64**			
Year	XOBS	YOBS	YCALC	RATIO	EXCESS			
Mean	16.27	19.77	18.65	**1.060**	**1.12**			

* Seeding in adjacent basin but not Boise target area
**Seeding in adjacent basin which affected control sites

blue = historical data (inches)
bold = seeded ratios
red = estimated data
green = observed minus predicted value

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.989196
R Square	0.978508
Adjusted R Square	0.977712
Standard Error	0.90045
Observations	29

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	996.7141	996.7141	1229.282	4.7E-24
Residual	27	21.89187	0.81081		
Total	28	1018.606			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-1.6798	0.603755	-2.78225	0.009728	-2.9186	-0.441	-2.9186	-0.441
X Variable 1	1.249555	0.035639	35.06112	4.7E-24	1.176429	1.322681	1.176429	1.322681

Precipitation - alternate (current) set, December - March

Regression (non-seeded) period:							
Year	XOBS	YOBS	YCALC	RATIO	EXCESS		
1982	18.07	28.49	24.17	1.18	4.32		
1983	21.80	27.68	29.06	0.95	-1.39		
1984	17.28	18.43	23.13	0.80	-4.70		
1985	9.48	11.62	12.90	0.90	-1.27		
1986	17.73	24.39	23.72	1.03	0.68		
1987	9.39	10.90	12.77	0.85	-1.87		
1988	11.06	16.60	14.96	1.11	1.64		
1989	14.34	18.07	19.27	0.94	-1.20		
1990	9.00	12.73	12.27	1.04	0.46		
1991	8.32	12.91	11.37	1.14	1.54		
1992	6.06	8.66	8.41	1.03	0.26		
1998	14.18	17.97	19.07	0.94	-1.10		
1999	15.01	23.21	20.16	1.15	3.05		
2000	14.36	19.89	19.30	1.03	0.59		
2001	7.10	8.77	9.78	0.90	-1.01		
Mean	12.88	17.36	17.35	1.00			
Seeded period:							
Year	XOBS	YOBS	YCALC	RATIO	EXCESS		
1993	14.83	22.17	19.92	**1.11**	**2.25**		
1994	8.59	13.41	11.72	**1.14**	**1.69**		
1995	15.29	24.34	20.52	**1.19**	**3.82**		
1996	16.72	25.34	22.40	**1.13**	**2.94**		
1997*	18.93	32.14	25.30	**1.27**	**6.85**		
2002	13.83	18.15	18.61	**0.98**	**-0.46**		
2003	14.03	21.26	18.87	**1.13**	**2.39**		
2004	14.12	18.44	18.99	**0.97**	**-0.55**		
2005	10.00	13.28	13.58	**0.98**	**-0.21**		
2008	15.28	18.62	20.51	**0.91**	**-1.89**		
2009	14.11	19.71	18.98	**1.04**	**0.73**		
Mean	13.67	19.77	18.40	**1.074**	**1.37**		
* Seeding in adjacent basin but not Boise target area							
blue = historical data (inches)							
bold = seeded ratios							
red = estimated data							
green = observed minus predicted value							

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.941421
R Square	0.886273
Adjusted R Square	0.877525
Standard Error	2.268727
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	521.45	521.45	101.309	1.67E-07
Residual	13	66.9126	5.147123		
Total	14	588.3626			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*
Intercept	0.456872	1.778129	0.25694	0.801247	-3.38454	4.298286	-3.38454
X Variable 1	1.312211	0.130371	10.06524	1.67E-07	1.030563	1.59386	1.030563

Apr 1 Snow - original set

Regression (non-seeded) period:						
Year	XOBS	YOBS	YCALC	RATIO	EXCESS	
1961	19.47	20.37	22.80	0.89	-2.43	
1962	23.53	27.96	27.74	1.01	0.21	
1963	12.01	16.70	13.70	1.22	3.00	
1964	22.11	25.27	26.02	0.97	-0.75	
1965	29.67	41.57	35.24	1.18	6.33	
1966	18.00	20.66	21.00	0.98	-0.34	
1967	23.77	26.38	28.04	0.94	-1.66	
1968	15.43	17.32	17.86	0.97	-0.54	
1969	29.96	34.27	35.59	0.96	-1.32	
1970	25.14	27.09	29.71	0.91	-2.63	
1971	33.27	39.98	39.63	1.01	0.35	
1972	29.10	37.26	34.54	1.08	2.71	
1973	17.84	19.46	20.81	0.93	-1.35	
1974	34.66	41.17	41.32	1.00	-0.16	
1975	28.74	33.26	34.11	0.98	-0.85	
1976	25.40	28.11	30.03	0.94	-1.92	
1977	6.09	5.66	6.46	0.87	-0.81	
1978	23.67	29.36	27.92	1.05	1.44	
1979	17.59	18.82	20.49	0.92	-1.67	
1980	26.50	28.47	31.37	0.91	-2.90	
1981	13.73	15.88	15.79	1.01	0.09	
1982	29.94	37.27	35.57	1.05	1.70	
1983	30.44	36.81	36.18	1.02	0.63	
1984	23.66	26.84	27.90	0.96	-1.06	
1985	21.97	23.60	25.85	0.91	-2.25	
1986	23.99	32.19	28.30	1.14	3.89	
1987	12.49	13.50	14.27	0.95	-0.77	
1988	13.26	17.79	15.21	1.17	2.58	
1989	22.71	27.07	26.75	1.01	0.32	
1990	12.64	15.11	14.46	1.04	0.65	
1991	13.59	15.62	15.61	1.00	0.01	
1992	11.41	12.58	12.97	0.97	-0.39	
1998	18.21	21.46	21.26	1.01	0.19	
1999	27.59	30.62	32.69	0.94	-2.07	
2000	19.66	22.60	23.02	0.98	-0.42	
2001	8.41	11.40	9.31	1.23	2.09	
Mean	21.27	24.98	24.99	1.00		
Seeded period:						
Year	XOBS	YOBS	YCALC	RATIO	EXCESS	

1993	20.29	27.09	23.79	**1.14**	**3.30**	
1994	11.63	13.76	13.23	**1.04**	**0.53**	
Year	XOBS	YOBS	YCALC	RATIO	EXCESS	
1995	21.84	30.91	25.69	**1.20**	**5.22**	
1996	22.89	28.13	26.96	**1.04**	**1.17**	
1997*	27.84	38.81	33.01	**1.18**	**5.80**	
2002	20.69	22.10	24.28	**0.91**	**-2.18**	
2003**	19.00	22.37	22.22	**1.01**	**0.15**	
2004**	16.69	19.52	19.40	**1.01**	**0.13**	
2005**	12.91	15.88	14.80	**1.07**	**1.08**	
2008**	24.20	25.73	28.56	**0.90**	**-2.83**	
2009**	19.09	21.62	22.32	**0.97**	**-0.70**	
Mean	18.92	22.71	22.12	**1.027**	**0.59**	
* Seeding conducted in adjacent basin, but not in target						
** Seeding conducted in adjacent basin which affected control sites						
blue = historical data (inches)						
bold = seeded ratios						
red = estimated data						
green = observed minus predicted value						
SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.976407					
R Square	0.95337					
Adjusted R Square	0.951999					
Standard Error	2.002906					
Observations	36					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	2788.687	2788.687	695.1498	3.24E-24	
Residual	34	136.3956	4.011634			
Total	35	2925.082				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.95884	1.039044	-0.92281	0.36261	-3.07043	1.152751
X Variable 1	1.219789	0.046264	26.36569	3.24E-24	1.125769	1.31381

Apr 1 Snow - alternate (current) set

Regression (non-seeded) period:						
Year	XOBS	YOBS	YCALC	RATIO	EXCESS	
1961	21.18	20.37	23.57	0.86	-3.21	
1962	26.08	27.96	29.69	0.94	-1.73	
1963	13.61	16.70	14.13	1.18	2.57	
1964	22.36	25.27	25.04	1.01	0.22	
1965	31.96	41.57	37.02	1.12	4.54	
1966	19.21	20.66	21.12	0.98	-0.46	
1967	25.71	26.38	29.23	0.90	-2.85	
1968	16.74	17.32	18.04	0.96	-0.72	
1969	29.69	34.27	34.19	1.00	0.07	
1970	24.21	27.09	27.36	0.99	-0.27	
1971	32.92	39.98	38.23	1.05	1.75	
1972	29.53	37.26	34.00	1.10	3.25	
1973	19.32	19.46	21.26	0.92	-1.80	
1974	34.08	41.17	39.67	1.04	1.49	
1975	27.70	33.26	31.71	1.05	1.54	
1976	23.66	28.11	26.67	1.05	1.45	
1977	8.34	5.66	7.56	0.75	-1.90	
1978	22.77	29.36	25.56	1.15	3.80	
1979	19.51	18.82	21.49	0.88	-2.67	
1980	26.97	28.47	30.80	0.92	-2.33	
1981	15.03	15.88	15.90	1.00	-0.03	
1982	30.52	37.27	35.23	1.06	2.03	
1983	32.86	36.81	38.15	0.96	-1.34	
1984	26.44	26.84	30.15	0.89	-3.30	
1985	23.16	23.60	26.04	0.91	-2.44	
1986	23.87	32.19	26.93	1.20	5.26	
1987	13.63	13.50	14.16	0.95	-0.66	
1988	15.77	17.79	16.82	1.06	0.97	
1989	25.20	27.07	28.59	0.95	-1.53	
1990	13.84	15.11	14.42	1.05	0.69	
1991	14.97	15.62	15.82	0.99	-0.20	
1992	9.97	12.58	9.58	1.31	3.00	
1998	19.78	21.46	21.83	0.98	-0.37	
1999	31.17	30.62	36.04	0.85	-5.42	
2000	20.97	22.60	23.31	0.97	-0.71	
2001	10.29	11.40	9.98	1.14	1.42	
Mean	22.31	24.98	24.98	1.00	0.00	
Seeded period:						
Year	XOBS	YOBS	YCALC	RATIO	EXCESS	
1993	22.51	27.09	25.24	**1.07**	**1.85**	
1994	13.59	13.76	14.10	**0.98**	**-0.35**	

1995	23.83	30.91	26.89	**1.15**	**4.02**	
Year	XOBS	YOBS	YCALC	RATIO	EXCESS	
1996	22.74	28.13	25.53	**1.10**	**2.61**	
1997*	30.00	38.81	34.58	**1.12**	**4.23**	
2002	22.86	22.10	25.67	**0.86**	**-3.57**	
2003	18.57	22.37	20.31	**1.10**	**2.05**	
2004	19.42	19.52	21.38	**0.91**	**-1.86**	
2005	14.70	15.88	15.49	**1.03**	**0.39**	
2008	24.33	25.73	27.51	**0.94**	**-1.78**	
2009	20.58	21.62	22.82	**0.95**	**-1.20**	
Mean	20.31	22.71	22.49	**1.010**	**0.22**	

* Seeding conducted in adjacent basin, but not in target

blue = historical data (inches)
bold = seeded ratios
red = estimated data
green = observed minus predicted value

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.96532
R Square	0.931843
Adjusted R Square	0.929838
Standard Error	2.421502
Observations	36

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2725.717	2725.717	464.848	2.08E-21
Residual	34	199.3649	5.863674		
Total	35	2925.082			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-2.85684	1.352896	-2.11165	0.042144	-5.60626	-0.10743
X Variable 1	1.248155	0.057891	21.56033	2.08E-21	1.130506	1.365804

APPENDIX D

STREAMFLOW REGRESSIONS WITH PRECIPITATION AND SNOWPACK

Precipitation (November - April) and Streamflow Gage #13185000 (April - July)

Regression period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS	
1982	47.23	997978	1053902	0.95	-55924	
1983	41.18	1005510	899827	1.12	105683	
1984	36.00	885500	768035	1.15	117465	
1985	25.70	534528	505725	1.06	28803	
1986	35.68	937515	759758	1.23	177757	
1987	17.53	303326	297532	1.02	5793	
1988	26.45	375412	524825	0.72	-149413	
1989	35.13	609285	745751	0.82	-136467	
1990	23.13	444187	440147	1.01	4040	
1991	22.65	385550	428051	0.90	-42500	
1992	19.45	291526	346556	0.84	-55031	
1993	36.10	752841	770582	0.98	-17740	
1994	20.00	308402	360563	0.86	-52161	
1995	40.65	876685	886457	0.99	-9771	
1996	43.18	999020	950761	1.05	48259	
1997	51.25	1139695	1156407	0.99	-16711	
1998	27.88	766619	561116	1.37	205503	
1999	39.40	886611	854623	1.04	31988	
2000	30.05	598720	616506	0.97	-17786	
2001	16.75	286036	277795	1.03	8241	
2002	30.83	581772	636243	0.91	-54471	
2003	32.38	650429	675717	0.96	-25288	
2004	29.50	511672	602500	0.85	-90828	
2005	19.60	459236	350376	1.31	108860	
2006	45.65	900793	1013792	0.89	-112998	
2007	26.00	482071	513365	0.94	-31294	
2008	32.33	700796	674444	1.04	26352	
Mean	31.54	654508	654495	1.00	13	
Precip					Streamflow	AF
1.7% incr	**32.08**		668150	**1.020864**	**2.1% incr**	**13,656**
1.5% incr	**32.01**		666544	**1.01841**	**1.8% incr**	**12,049**
1.9% incr	**32.14**		669757	**1.023319**	**2.3% incr**	**15,262**
					Total	**40,967**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.94248**
R Square	0.888268

Adjusted R Square	0.883799
Standard Error	88063.75
Observations	27

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1.541E+12	1.541E+12	198.7502	2.1114E-13
Residual	25	1.939E+11	7.755E+09		
Total	26	1.735E+12			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	**-148777.4**	59446.244	-2.5027224	0.019225	-271209.19	-26345.7
X Variable 1	**25467.44**	1806.4729	14.097878	2.11E-13	21746.9373	29187.9334

Precipitation (November - April) and Streamflow Gage #13186000 (April - July)

Regression period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS	
1982	47.23	736097	715560	1.03	20537	
1983	41.18	767389	597611	1.28	169778	
1984	36.00	620206	496721	1.25	123484	
1985	25.70	332096	295916	1.12	36180	
1986	35.68	643004	490385	1.31	152619	
1987	17.53	180939	136539	1.33	44400	
1988	26.45	228150	310538	0.73	-82388	
1989	35.13	388492	479663	0.81	-91170	
1990	23.13	251817	245715	1.02	6102	
1991	22.65	214329	236454	0.91	-22125	
1992	19.45	143821	174068	0.83	-30248	
1993	36.10	467366	498671	0.94	-31305	
1994	20.00	163376	184791	0.88	-21415	
1995	40.65	621620	587376	1.06	34244	
1996	43.18	620089	636603	0.97	-16514	
1997	51.25	767868	794030	0.97	-26162	
1998	27.88	489215	338319	1.45	150896	
1999	39.40	516401	563007	0.92	-46605	
2000	30.05	329217	380722	0.86	-51506	
2001	16.75	152573	121430	1.26	31143	
2002	30.83	307407	395831	0.78	-88425	
2003	32.38	361776	426050	0.85	-64273	
2004	29.50	263193	370000	0.71	-106807	
2005	19.60	283621	176993	1.60	106628	
2006	45.65	634024	684854	0.93	-50831	
2007	26.00	212808	301765	0.71	-88957	
2008	32.33	367795	425075	0.87	-57280	
Mean	31.54	409803	409803	1.00	0.02	
Precip					Streamflow	AF
1.7% incr	**32.08**		420257	**1.025509**	**2.6% incr**	**10,454**
1.5% incr	**32.01**		419027	**1.022508**	**2.3% incr**	**9,224**
1.9% incr	**32.14**		421487	**1.02851**	**2.9% incr**	**11,684**
					Total	**31,361**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.918139**
R Square	0.842979

Adjusted R Square	0.836698
Standard Error	82035.9
Observations	27

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	9.032E+11	9.0325E+11	134.2145	1.52138E-11
Residual	25	1.682E+11	6729889413		
Total	26	1.071E+12			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	**-205122.4**	55377.229	-3.7040923	0.001055	-319173.8222	-91070.90715
X Variable 1	**19495.66**	1682.8223	11.5850971	1.52E-11	16029.82457	22961.49443

Snowpack (April 1) and Streamflow Gage #13185000 (April - July)

Regression period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS	
1982	41.70	997978	1036253	0.96	-38275	
1983	41.68	1005510	1035608	0.97	-30099	
1984	30.83	885500	755819	1.17	129681	
1985	27.25	534528	663631	0.81	-129103	
1986	37.10	937515	917633	1.02	19882	
1987	14.95	303326	346451	0.88	-43125	
1988	19.98	375412	476030	0.79	-100618	
1989	32.30	609285	793855	0.77	-184571	
1990	16.43	444187	384486	1.16	59700	
1991	17.88	385550	421878	0.91	-36327	
1992	13.20	291526	301323	0.97	-9798	
1993	31.73	752841	779028	0.97	-26186	
1994	15.35	308402	356765	0.86	-48364	
1995	33.88	876685	834470	1.05	42216	
1996	31.65	999020	777094	1.29	221926	
1997	45.68	1139695	1138756	1.00	939	
1998	24.05	766619	581112	1.32	185506	
1999	35.98	886611	888622	1.00	-2012	
2000	25.58	598720	620438	0.96	-21717	
2001	12.85	286036	292298	0.98	-6262	
2002	26.60	581772	646869	0.90	-65097	
2003	24.25	650429	586270	1.11	64159	
2004	23.13	511672	557259	0.92	-45588	
2005	17.63	459236	415431	1.11	43805	
2006	37.33	900793	923435	0.98	-22641	
2007	18.25	482071	431548	1.12	50523	
2008	29.03	700796	709403	0.99	-8607	
Mean	26.90	654508	654510	1.00	-1.88	
Snow					Streamflow	AF
1.7% incr	**27.35**		666301	**1.018015**	**1.8% incr**	**11,791**
1.6% incr	**27.33**		665607	**1.016955**	**1.7% incr**	**11,097**
1.5% incr	**27.30**		664913	**1.015895**	**1.6% incr**	**10,404**
					Total	**33,292**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.943129**
R Square	0.889492
Adjusted R Square	0.885071

Standard Error	87580.27
Observations	27

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1.543E+12	1.543E+12	201.2274	1.839E-13
Residual	25	1.918E+11	7.67E+09		
Total	26	1.735E+12			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	**-39065.19**	51716.856	-0.7553666	0.457087	-145577.97	67447.597
X Variable 1	**25786.94**	1817.8425	14.185463	1.84E-13	22043.023	29530.851

Snowpack (April 1) and Streamflow Gage #13186000 (April - July)

Regression period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1982	41.70	736097	708599	1.04	27498
1983	41.68	767389	708095	1.08	59294
1984	30.83	620206	489100	1.27	131106
1985	27.25	332096	416942	0.80	-84847
1986	37.10	643004	615754	1.04	27251
1987	14.95	180939	168681	1.07	12258
1988	19.98	228150	270105	0.84	-41955
1989	32.30	388492	518871	0.75	-130379
1990	16.43	251817	198452	1.27	53365
1991	17.88	214329	227719	0.94	-13390
1992	13.20	143821	133359	1.08	10462
1993	31.73	467366	507265	0.92	-39900
1994	15.35	163376	176754	0.92	-13378
1995	33.88	621620	550661	1.13	70960
1996	31.65	620089	505751	1.23	114337
1997	45.68	767868	788830	0.97	-20962
1998	24.05	489215	352354	1.39	136861
1999	35.98	516401	593047	0.87	-76645
2000	25.58	329217	383134	0.86	-53918
2001	12.85	152573	126295	1.21	26278
2002	26.60	307407	403823	0.76	-96416
2003	24.25	361776	356391	1.02	5385
2004	23.13	263193	333684	0.79	-70491
2005	17.63	283621	222673	1.27	60948
2006	37.33	634024	620295	1.02	13729
2007	18.25	212808	235288	0.90	-22480
2008	29.03	367795	452769	0.81	-84974
Mean	26.90	409803	409803	1.00	-0.12

Snow				Streamflow	AF
1.7% incr	**27.35**	419032	**1.02252**	**2.3% incr**	**9,229**
1.6% incr	**27.33**	418489	**1.021195**	**2.1% incr**	**8,686**
1.5% incr	**27.30**	417946	**1.019871**	**2.0% incr**	**8,143**
				Total	**26,058**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.939419**
R Square	0.882507

Adjusted R Square	0.877808
Standard Error	70962.79
Observations	27

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	9.456E+11	9.456E+11	187.7792	3.96997E-13
Residual	25	1.259E+11	5035717673		
Total	26	1.071E+12			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	**-133068**	41904.1	-3.1755365	0.003945	-219371.044	-46764.94803
X Variable 1	**20183.87**	1472.925	13.7032539	3.97E-13	17150.32169	23217.40915

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