R-93-14

EVALUATION OF IDAHO'S 1992–1993 WINTER CLOUD SEEDING PROGRAM

OCTOBER 1993

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Denver Office
Research and Laboratory Services Division
Water Augmentation Group

7-2090 (4-81)
Bureau of Reclamation

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. R-93-14	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Evaluation of Idaho's 1992-1993 Winter Cloud Seeding Program		5. REPORT DATE October 1993 6. PERFORMING ORGANIZATION CODE D-3720
7. AUTHOR(S) Arlin Super		8. PERFORMING ORGANIZATION REPORT NO. R-93-14
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bureau of Reclamation Denver Office Denver CO 80225		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. 13. TYPE OF REPORT AND PERIOD COVERED
12. SPONSORING AGENCY NAME AND ADDRESS Same		14. SPONSORING AGENCY CODE DIBR

15. SUPPLEMENTARY NOTES

Microfiche and hard copy available at the Denver Office, Denver, Colorado

16. ABSTRACT

At the request of the State of Idaho, the Bureau of Reclamation performed an independent evaluation of a precipitation management (cloud seeding) program conducted during the 1992-1993 winter. The State asked Reclamation to evaluate the program statistically and physically. For various reasons, neither approach was expected to provide definitive answers concerning program effectiveness, but a "first look" evaluation was judged useful for planning future precipitation management activities within the State. The State also requested that Reclamation make recommendations for improving the operational seeding program in the future.

A target-control analysis was performed which provided no convincing statistical evidence that the program succeeded in its goal of enhancing the mountain snowpack to any beneficial extent. However, this statistical analysis approach cannot discern a limited increase from a single winter's seeding. An approximate upper limit of snowfall production caused by seeding was estimated by physical reasoning for the Boise target area. This estimate was not encouraging. Reclamation recommended several modifications for the Idaho operational seeding design.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS-- atmospheric research/ meteorology/ weather modification/ orographic clouds/ cloud seeding/ meteorological instruments/

b. IDENTIFIERS-- State of Idaho/

c. COSATI Field/Group 04B ***COWRR:*** 0402.1 ***SRIM:***

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (THIS REPORT) *UNCLASSIFIED*	21. NO. OF PAGES 48
	20. SECURITY CLASS (THIS PAGE) *UNCLASSIFIED*	22. PRICE

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by

Arlin B. Super

Water Augmentation Group
Research and Laboratory Services Division
Denver Office
Denver, Colorado

October 1993

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

U.S. Department of the Interior
Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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1. INTRODUCTION

The State (State of Idaho), in cooperation with local water interests, sponsored a precipitation management program during the winter of 1992-1993. This "cloud seeding" program was designed and conducted by a private firm, NAWC (North American Weather Consultants), of Salt Lake City, Utah.

The State requested that Reclamation (Bureau of Reclamation) perform an independent evaluation of the seeding program. Reclamation was asked to statistically evaluate the program by comparing target and control areas. Reclamation was also asked to physically evaluate the program in terms of the reasonableness of seeding generator placement, overall output of effective IN (ice nuclei), general conduct of the program, and other factors. Neither the statistical nor the physical approach was expected to provide definitive answers concerning program effectiveness because of the limited duration of the seeding, the lack of randomization, and the lack of supporting physical measurements. Nevertheless, a "first look" evaluation was judged useful for planning future precipitation management activities within the State. The State also requested that Reclamation make recommendations for improving the operational seeding program in the future.

2. LIMITATIONS OF STATISTICAL EVALUATION

Statistical evaluation of cloud seeding projects is a challenging process which has significant potential for serious bias and error. The main problem is that natural weather has considerable variability. In particular, precipitation varies markedly with time and space. (The terms "precipitation" and "snowfall" will be used synonymously herein because this report deals with Idaho wintertime precipitation at high elevations). The amount of seasonal snowfall change expected from successful seeding of winter orographic (mountain-induced) clouds is on the order of 10 percent (American Meteorological Society, 1992). But 400-percent variations in seasonal mountain snowpack accumulation are commonly found in the intermountain West over periods of a few decades. The challenge is to detect the relatively weak "seeding signal" within the large natural background "noise."

Elaborate schemes have been developed to minimize statistical errors in cloud seeding experiments. The Weather Modification Advisory Board (1978) devoted an entire volume to statistical issues. Statistical experiments are designed to minimize errors in the evaluation process, employing such features as randomization and "blindness." Randomization refers to the process of selecting only some of the experimental units (e.g., storms, days, entire winters) for treatment (seeding) by random decision. Other units are left untreated, but have the same measurements taken to serve as the "controls" or basis for comparison with treated units. Blindness refers to the experimenters being unaware of which experimental units are actually seeded and which receive a placebo treatment until after analyses are complete. Statistical experiments also require precise definition of experimental units.

Further discussion of such features is beyond the scope of this report, but operational programs do not incorporate them, and so are much more difficult to statistically evaluate with any degree of confidence. Readers interested in the details of statistical design of experimental programs may refer to such sources as Dennis (1980), Gabriel (1981), and the Weather Modification Advisory Board (1978).

As pointed out by Dennis (1980), some statisticians have argued that the uncertainties in operational cloud seeding programs make all analyses of these programs essentially useless. However, others hold the view that such analyses can provide useful information if potential pitfalls are borne in mind and care is taken to avoid insupportable claims.

This author maintains that operational programs can produce useful information, and has supported this point of view by undertaking the analysis to be presented. However, the reader should not expect anything approaching "scientific proof" from statistical analysis of an operational program, and certainly not from the Idaho program at this time because seeding was conducted for less than a single winter. At best, the analysis will produce some suggestions or "hints" of possible seeding effects. An expectation of more specific results is unrealistic, and the reader should interpret any statistical suggestions with care. No justification exists to claim any level of statistical significance for suggested results from a single season of operational, nonrandomized seeding.

3. OVERVIEW OF TARGET-CONTROL EVALUATION

3.1 Choosing Measurement Sites

The most common approach used to evaluate operational seeding is the "target-control" method, which will be used here. In the case of the Idaho program, this method involves comparing snowfall observations from two or more areas. The "target" is that area intended to be affected by seeding with the purpose of increasing its snowfall. Throughout this report, target areas are as defined by NAWC in their reports to the program sponsors. The "control" refers to one or more measurement locations (sites) assumed to be unaffected by seeding. Control areas should be located upwind or crosswind from the target to increase the likelihood that they remain unaffected by seeding. Control sites may be chosen over a widespread region so long as their snowfall measurements have a reasonable relationship with similar measurements made in the target area.

Control areas are usually chosen near target areas to increase the degree of association between target and control snowfall measurements. However, such a choice often involves a "trade-off" between selecting controls close to the target, and increasing the risk that seeding will contaminate the control. Any such contamination would be unknown in the absence of special measurements (e.g., silver-in-snow concentrations). Contamination would

reduce the detectability of any seeding signal, presuming any seeding effect occurred in the same direction (e.g., increased snowfall) in both target and control.

Choosing control measurement sites involves more work than simply picking locations as near the target as possible while remaining reasonably certain that contamination of the control sites is minimal or nonexistent. As will be discussed further, the most important factor involves maximizing the degree of association between target and control measurements so the latter can be used to predict the former with good accuracy. Although the degree of association tends to decrease with increasing distance, many other factors influence target-control relationships in complex ways, particularly in mountainous terrain. Some of the important factors include shape and orientation of the terrain for prevailing storm tracks, elevation, blocking by nearby upwind mountain ranges, and local topography and forest cover around the measurement sites.

3.2 Target-Control Relationships

Observations from nonseeded winters prior to the 1992-1993 (hereafter 1993) seeded winter were used to establish mathematical relationships between the target and control snowfall observations. This procedure assumes that the relationship did not change during the seeded period, which is probably a valid assumption but cannot be proven. Changes in such relationships can occur over several years because of such factors as forest growth, which may affect snowfall on the measurement sites.

The relationship between any given winter's target and control snowfall may depart from the long-term relationship for completely natural reasons. For example, if the frequency of a particular storm track is much higher or lower than usual during a particular winter, the target-control relationship may differ markedly from more typical winters. One to a few particularly wet storms, concentrated over either the target or control area but not both, can produce a marked natural change in the relationship for a given winter.

Target-control relationships were established for a population of many winters. These relationships were used with the control snowfall measurements from the 1993 seeded winter to predict the target area's natural snowfall. Departures in seeded area snowfall from these predictions were examined. A large departure in target area snowfall from the predicted amount might be related to seeding. However, as already pointed out, such a departure might also be partially or totally a natural phenomena.

Examination of the variability ("scatter") of individual departures from many nonseeded winters can provide some idea of the probability that a large seeded winter departure was caused by seeding. As previously noted, claims of a specific level of statistical significance for any departure are not valid without randomization. Unfortunately, such claims are often made in analysis of operational projects.

3.3 Applying The Target-Control Approach

Figure 1, which illustrates the target-control approach, is a plot of the April 1 SWE (snow water equivalent) measured at two SCS (Soil Conservation Service) snow measuring sites: the Atlanta Summit site east of Boise (target) and the Bear Saddle site northwest of Boise (control). The pairs of April 1 observations are plotted as a point for each of 30 years as labeled. The straight line through the middle of the points is the "linear regression" equation, or the line which is mathematically calculated as the best "fit" to the 30 data points.

Figure 1 shows considerable scatter of points representing individual years. In general, when the SWE is high (low) at the control site, it is high (low) at the target site. The linear regression line provides the best estimate of target SWE for any given control SWE. But the figure shows that measurements in individual years often depart from the line by a few to several inches.

Another mathematical calculation provides the "correlation coefficient," represented by "R" or "R-value", which is a measure of the scatter of the points. The higher the value of R, the less the scatter, and the better the predictability of natural target SWE. If all the points fit exactly on a straight line, R would equal 1.0, indicating a perfect correlation. If the points had no correlation, forming a pattern similar to shotgun pellet holes in a paper target, the value of R would equal 0.0. In the case of figure 1, $R = 0.84$, a low value for attempting a target-control analysis with 30 data points. Because the nonseeded 1965 winter (the point labeled "65") is plotted over 20 inches above the regression line, seeding would have to result in a similar departure to demonstrate effectiveness. But such an indication would require over a 60-percent increase in snowfall, several times greater than the approximately 10- to 15-percent increases suggested by some well-designed and well-operated projects. Therefore, no reasonable chance exists to detect a real seeding effect with the target-control relationship shown on figure 1. But figure 1 was chosen to illustrate the points made, not because it indicated a high target-control relationship. Fortunately, much better relationships exist, as will be shown.

Averaging observations from a number of snow measurement sites often results in higher R-values and more stable results. The appropriate approach for this type of target-control analysis is to select as many observing sites for averaging as possible so long as the selection process is physically justified. At the same time, a high R-value should be sought, although attempting to increase it from, say, 0.955 to 0.960 has little justification because of natural variability. Calculating the highest possible R-value by selectively choosing particular sets of target and control sites offers no guarantee that a similarly high value will result from a different time period. Most likely, a lower R-value would be calculated from another period of observations. A more stable result would be expected from averages of more measurement sites, even if the R-value is slightly reduced.

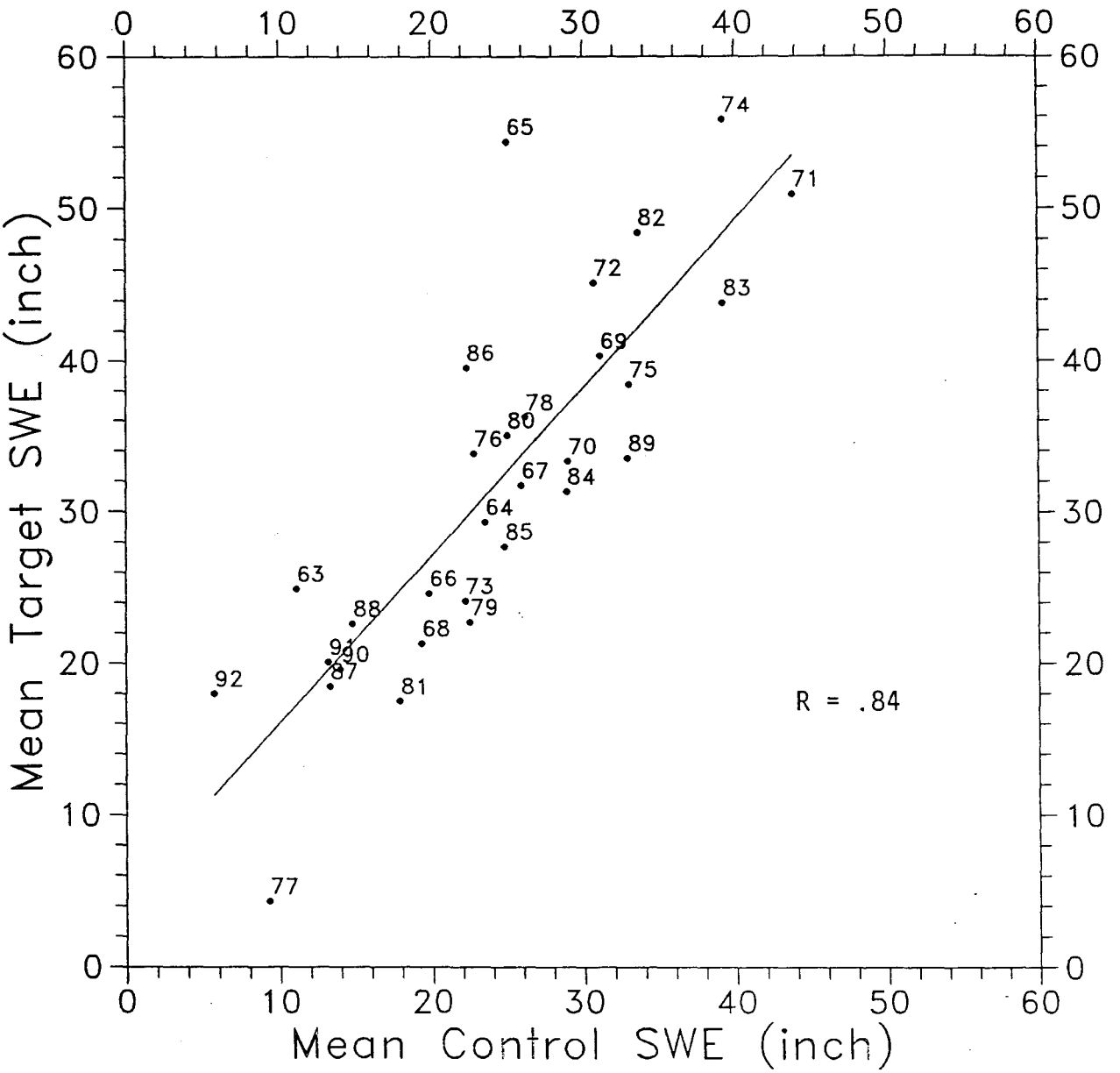

Figure 1. - Plot of April 1 SWE for the 30 years indicated: Atlanta Summit target versus Bear Saddle control. The straight line is the linear regression equation. The correlation coefficient, *R*, is also shown.

None of the years shown on figure 1 were seeded, so only natural variability is being displayed. Suppose, however, that the year 1965 had been seeded and the other 29 years had not been seeded. In that case, one would naturally suspect that seeding at least partially caused the unusually large 1965 departure. However, suppose that 1967 had been the only seeded year. Then one would suspect that seeding had little if any effect. As a final example, suppose that only 1989 had been seeded. Then one might suspect that seeding had decreased the snowfall. The reader should note that the suspicions associated with each of these examples do not constitute scientific proof.

On the other hand, humans base decisions every day on suspicions or beliefs rather than on proof. Given the vast number of circumstances where scientific proof does not exist, a person often has little choice. The field of medical care is full of such examples. So even a suggestion of possible seeding effectiveness, or lack thereof, may interest those considering future cloud seeding operations.

4. SPECIFIC IDAHO TARGET AREAS

The Idaho cloud seeding program actually involved three projects. The intended target areas were located in the Boise River drainage area east of Boise, the upper Snake River drainage area of eastern Idaho and extreme western Wyoming, and the Bear River drainage area of southeastern Idaho. The upper Snake target is actually separated into two more-or-less continuous areas. The first lies on the south side of the Montana-Idaho border. The second "wraps around" the north and east sides of the Bear target. Because this second portion of the upper Snake target borders the Bear target, they cannot realistically be separated. Seeding in one project might easily affect the adjoining project.

Seeding operations commenced first for the Boise target with the initial seeding done on December 16, 1992. The first seeding for the upper Snake took place on January 18, 1993, and the first seeding for the Bear occurred on January 22, 1993. However, complete networks of AgI seeding generators were not in operation for any of the three target areas on the dates noted, but were operational in the Boise by late December, and in the other two targets by about February 1. Seeding continued until April 24 in the Boise, April 30 in the upper Snake, and April 13 in the Bear.

Not every storm was seeded. A set of seeding criteria was established by NAWC, and they attempted to seed only those storm conditions that met their criteria. Because of the scarcity of observations in mountainous terrain, NAWC relied primarily on forecasts made by their meteorologists in deciding when to seed.

Most attention will be focused on analyses of the Boise target for the following reasons. The Boise target, which had the longest period of seeding, could be expected to have the strongest seeding signal. Very good target-control relationships (high R-values) will be shown between

the Boise target and its upwind controls. No known contamination occurred in the Boise controls because of upwind seeding, and no seeding is known to have occurred in the Boise drainage for the 30-year period prior to the 1993 winter.

Some potential control sites for the other two targets conceivably could have been affected by the Boise target seeding and/or by the widespread operational seeding in Utah. Much or all of the high terrain in Utah just south of the Idaho border has been seeded in recent winters, which could affect both target and control areas in southeastern Idaho. Moreover, the Bear River drainage has been seeded frequently in the past (Griffith et al., 1983), including during the 1988-1989 and 1989-1990 winters. The frequent seeding has reduced the number of nonseeded winters available for comparison. For all these reasons the Boise seeding signal, if it exists, should be the most detectable.

5. SNOWPACK SNOW WATER EQUIVALENT OBSERVATIONS

The Idaho cloud seeding program was intended to increase the high elevation snowfall, resulting in a snowpack with higher SWE, which could result in more spring and summer streamflow. Accordingly, measurements of high elevation SWE are of prime interest in evaluating the seeding.

5.1 Sampling Methods

The SCS has operated a large network of manually-sampled snow courses in the mountains of Idaho and nearby States for several decades. More recently, snow pillows have been incorporated into the observing network. Since about 1980, a radio-telemetry system known as SNOTEL has been become increasing important. The system currently provides daily measurements of SWE from snow pillows, of precipitation from gauges, and of maximum, minimum, and average air temperature.

At several locations, snow courses continued to be manually sampled on a monthly or bi-monthly basis while similar observations were obtained nearby with the SNOTEL system. The approach has been to attempt to demonstrate a good relationship between the two methods over a period of approximately a decade. Once that relationship was established, the snow course was discontinued and future measurements were made automatically by SNOTEL. Accordingly, the snow course has been discontinued at most paired snow course and snow pillow sites. Older snow course data have been adjusted with the relationship established between the two methods so the measurements appear to be from one site. In reality, many SCS snow observing sites are now a hybrid, consisting of estimates based on snow course measurements prior to approximately 1980, and on snow pillow measurements since whenever the pillow was installed.

A further complication is that many observing sites have been discontinued in recent years as a cost-savings measure. Unless some special need could be shown, a number of sites were judged to be redundant and eliminated.

These changes in SCS observing sites and method are mentioned because they required the implementation of a tedious search for currently valid data. The most recent map of Snow Survey Data Sites for Idaho was published in 1988. NAWC supplied target area maps, which also indicated individual AgI generator locations. The target areas were traced on the Snow Survey Map. All available snow data measuring sites were then identified, as were potential control sites.

5.2 Choosing Control Sites

Potential control sites were chosen as close as possible to the target areas while remaining generally upwind; that is, to the southwest, west, or northwest of the targets. The approach was to proceed upwind from the targets until several measurement sites were identified, but no further upwind than necessary. In most cases, the degree of association (correlation) between snow measurement sites tends to decrease with increasing distance. However, exceptions exist to this general rule as will be shown.

Choosing control sites is a subjective process in terms of deciding how far upwind is too far. In practice, existing topography determines where the snow measuring sites are. Once all sites have been chosen for the first few mountain ranges upwind in a particular direction, resulting in several sites, little reason exists to search further upwind unless resulting R-values are mediocre.

Well over 100 snow measurement sites were identified for the three seeding projects from the map of Idaho Snow Survey Data Sites in Idaho, Montana, and Wyoming. Sites were either within the target areas (in a few cases just over the divide forming the target basin boundary), or were possible control sites. In the case of the Boise target, four sites were chosen a short distance downwind (east) from the target area for examination of possible downwind effects. Downwind sites were not examined for the other project areas.

Once measurement site names were identified, all existing data for each site was downloaded from the SCS's computerized data base in Portland, Oregon. Many sites on the 1988 map were found to have been discontinued, so such sites were excluded from further consideration. Several snow measurement sites were found that had records extending back to the early 1960's but not earlier. Therefore, another criterion for keeping a site was that it had to have records for April 1 SWE from at least 1963 through 1993. This criterion provided a minimum of 30 nonseeded winters. At a few snow measurement sites which had only one winter of missing data, the missing point was estimated using a regression equation calculated for other years with a nearby station.

Although seeding continued into mid- or late April in the three projects, the seasonal snowpack is known to reach its maximum on or soon after April 1 in most years. Using measurements after April 1 will result in lower correlation coefficients between many snowpack measurement locations because of the added variability ("variance") caused by snow melt at some sites during some years. Consequently, April 1 observations were mainly used in the target-control evaluations.

Any sites lower than 6000 feet elevation (all elevations are above mean sea level) were excluded because of the possibility of melting significantly affecting the measurements. Some of these sites had frequent zero SWE readings by April 1. Finally, three sites that were aerial markers were excluded. Such sites have only depth readings. Their SWE is estimated by using density observations from snow courses in the vicinity. SWE observations from the three aerial marker sites were not highly associated with nearby snow course or pillow observations. A final list of 76 acceptable sites was prepared of all snowpack measurement sites that met the stated criteria for April 1 observations, as given in appendix A.

6. EVALUATION OF THE BOISE TARGET AREA

6.1 Control Sites

Table 1 lists the available sites for the Boise project in the following order: target sites, control sites west or northwest of the target, control sites southwest of the target, and sites within 25 miles east (generally downwind) of the target. The SCS site name and identification number is given for each location along with its elevation (feet), latitude (degrees-minutes) and longitude (degrees-minutes). The number to the left of the site name is the alphabetical rank out of all 76 sites used in analysis of all three projects, with the Idaho sites listed first, followed by Montana and Wyoming sites. The last four sites are Idaho control sites that were added late in the analysis process. Sites will be referred to by the number left of their name.

Figure 2 shows the locations of the SWE measurement sites listed in table 1. Each SWE measurement site is shown by a star with a number next to it corresponding to table 1 and appendix A. The boundary of the target area and the locations of the 19 AgI generators are shown as provided by NAWC. The 7000-foot contour is shown within the target area where the terrain elevation generally increases eastward.

Some of the snow measurement sites require clarification. Site 8 lies immediately west of the NAWC designated target area and might be subject to contamination by seeding with some wind directions. Similarly, site 3 lies due north of the center of the target area and might be affected by seeding with southerly flow. However, this potential problem may be minimal. According to the NAWC seeding logs, the 19 available AgI generators for the Boise project were never all used during a single storm. An average of 8.4 generators were

operated during the 22 seeded storms. One of the NAWC cloud seeding criterion is "low-level wind directions and speed that would favor the movement of the AgI (silver iodide) particles from their points of release into the intended target area." If only those generators were operated that were appropriate for the prevailing low-level wind directions, any seeding effect for site numbers 3 and 8 should have been minimized.

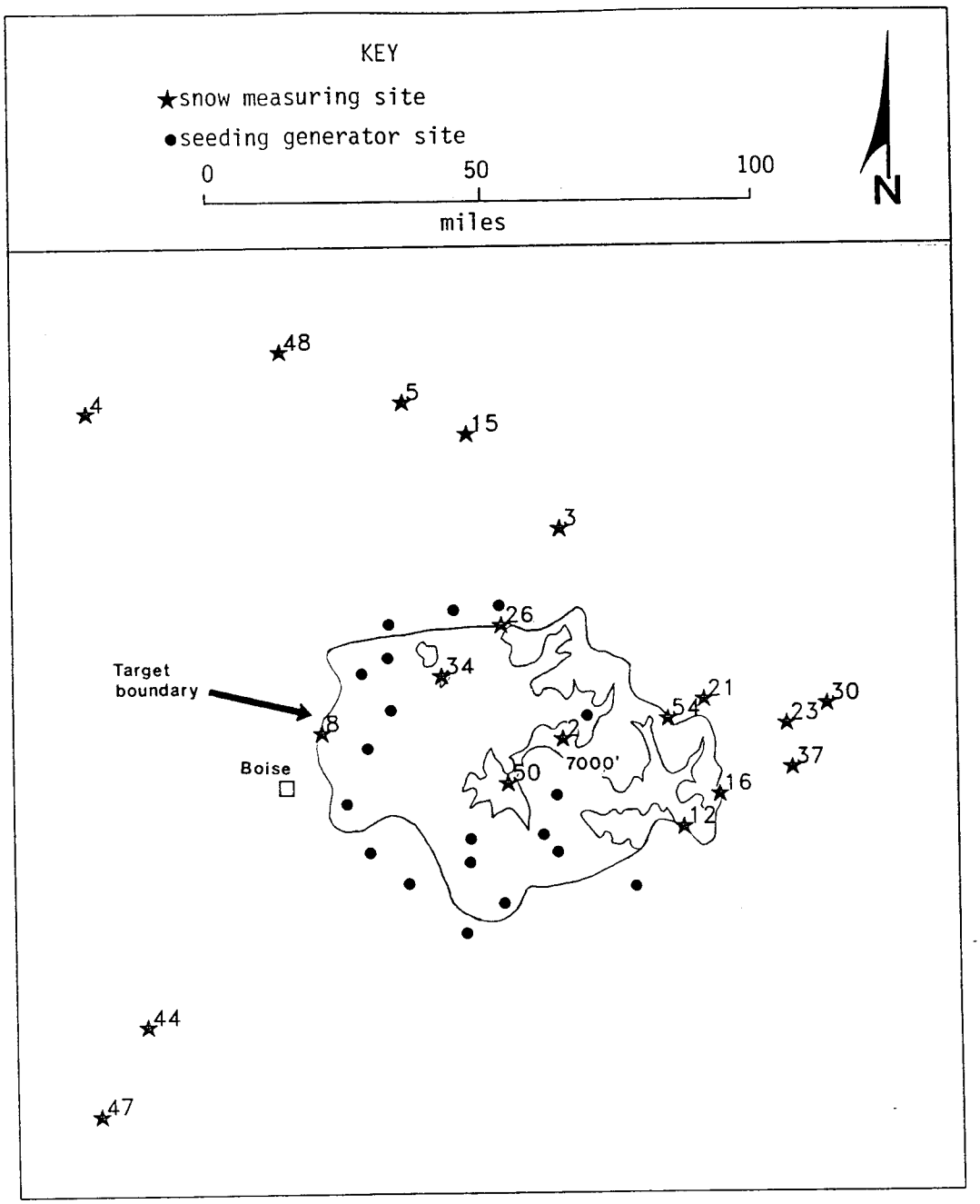

Figure 2. - Map of the NAWC-designated Boise target area showing the locations of AgI seeding generators and snow measurement sites. Numbers by the latter refer to the table 1 listing. The 7000-foot contour is shown within the target area.

Site numbers 34 and 35 are located at essentially the same place. One is a snow course still being manually sampled, and the other is a nearby snow pillow. As might be expected, the R-value between the two is very high, 0.996.

Table 1. - Listing of SCS snow measurement sites used in analysis of the Boise seeding program for target sites, control sites, and sites immediately downwind from the Target Area.

Site No.	Site Name	SCS I.D.	Elevation (feet)	Latitude (DD-MM)	Longitude (DD-MM)
	(Target Sites)				
2	Atlanta Summit SNOTEL	15F04	7580	43-45	115-14
12	Couch Summit #2	14F18	6840	43-31	114-48
16	Dollarhide Summit SNOTEL	14F08	8420	43-36	114-40
26	Jackson Peak SNOTEL	15E09	7070	44-03	115-27
34	Moores Creek Summit	15F01	6100	43-55	115-40
35	Moores Creek Summit SNOTEL	15F01	6100	43-55	115-40
50	Trinity Mountain SNOTEL	15F05	7770	43-38	115-26
54	Vienna Mine Pillow	14F04	8960	43-48	114-51
	(N.W. Controls)				
3	Banner Summit (due North)	15E11	7040	44-18	115-14
4	Bear Saddle SNOTEL	16E10	6180	44-36	116-58
5	Big Creek Summit Pillow	15E02	6580	44-38	115-48
8	Bogus Basin (due West)	16F02	6340	43-46	116-06
15	Deadwood Summit SNOTEL	15E04	6860	44-33	115-34
48	Squaw Flat Pillow	16E05	6240	44-46	116-15
	(S.W.Controls)				
44	Silver City	16F03	6400	43-00	116-44
47	South Mountain Pillow	16G01	6500	42-46	116-54
	(Downwind from Target)				
21	Galena Summit SNOTEL	14F12	8780	43-51	114-43
23	Graham Ranch	14F05	6270	43-47	114-25
30	Lost-Wood Divide Pillow	14F03	7900	43-50	114-16
37	Mount Baldy	14F09	8920	43-40	114-24

6.2 Target-Control Relationships

A straightforward approach relates all eight target sites listed in table 1 with all eight controls from southwest through northwest. Figure 3 shows a plot of the April 1 SWE data pairs averaged for these sites for the 30-year period 1963 through 1992, which will be the period used henceforth unless otherwise stated. The center of the three straight lines is the linear regression equation calculated for the 30 nonseeded data pairs.

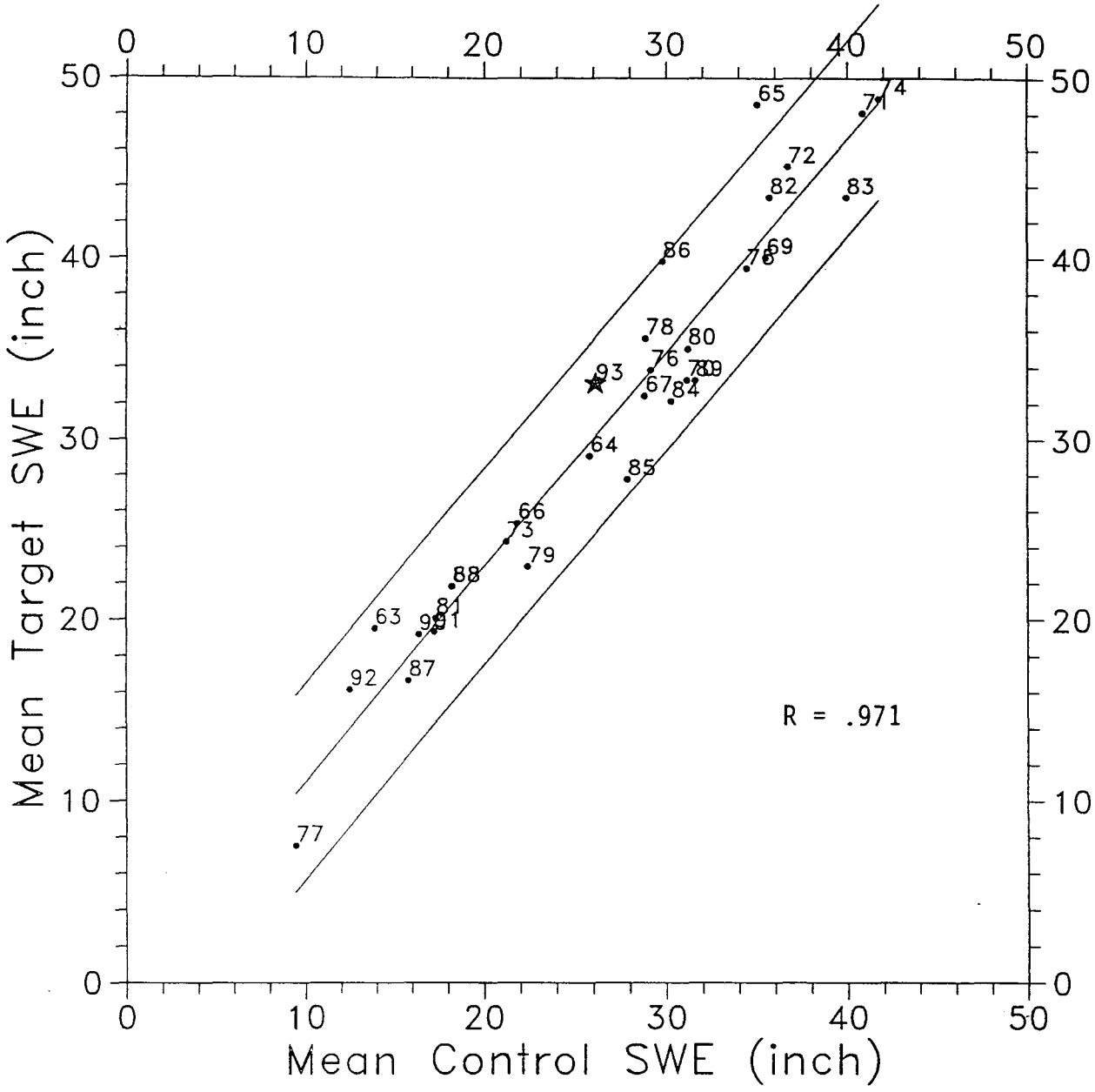

Figure 3. - Plot of average April 1 SWE for the years indicated for eight Boise target sites versus eight upwind control sites. The linear regression equation and ± two standard errors of estimate are plotted for the 1963-1992 nonseeded winters.

A high correlation coefficient (R-value) of 0.971 resulted from the data of figure 3. Therefore, a reasonably high degree of predictability exists for natural (nonseeded) target snowpack SWE on April 1 using the average of the control observations and the regression equation.

The upper and lower lines parallel to the linear regression equation represent ± 2 standard errors of estimate. For a normal distribution of data points, 95 percent of all points would be expected to lie within the two outer lines. Therefore, a point above (or below) the line would have approximately a 5 percent probability of being from the same population as the points between the lines. In other words, such an outlying point would be suspected of being significantly "different" than the other points. Such a difference could raise the suspicion that it was caused by seeding. In fact, the only year outside the standard error of estimate lines is 1965, a nonseeded year. Having 1 point in 30 outside the lines would be about what might be expected as 1/30 = 0.033 or 3.3 percent, close to the 5 percent typical for a normal distribution.

It should be understood that the 1993 observations do not enter into any of the calculations of the regression equation, standard errors of estimate, or correlation coefficient on figure 3 or similar figures to follow. Such calculations are based only on the 30 nonseeded winters 1963-1993.

The 1993 point for the average target and control data is plotted as a star labeled "93." The 1993 departure lies 2.9 inches of SWE above the regression line fitted to the 30 nonseeded winters. This departure is equivalent to 9.6 percent more snowfall than predicted. But the 1993 observation lies about one standard errors of estimate above the regression line; that is, about midway between the regression line and the upper two standard errors line. For a normal distribution, 68 percent of all points can be expected to fall within ±1 standard error of estimate. Consequently, although the 1993 departure deviated in the desired direction, it has no statistical significance.

Figure 3 illustrates one of the problems of attempting to evaluate a single winter's seeding. Even though the 1993 winter's departure is near 10 percent, a figure often quoted as about what successful winter orographic cloud seeding might produce, the departure is well within the natural winter-to-winter variation. Moreover, the R-value calculated for the particular data set is quite respectable. Correlation coefficients based on April 1 SWE observations are seldom higher than 0.97 unless the measurement sites are very near one another. Therefore, one cannot expect much better predictability than provided by the data of figure 3. A number of winters with <u>consistent</u> departures well above the regression line (SWE increases) would be needed before the evidence would strongly suggest a seeding effect.

Had only the year 1965 been seeded, one would might have concluded from figure 3 that seeding had been very effective. Conversely, had only 1985 been seeded, one might have concluded that seeding decreased the snowpack. Of course, both conclusions would have been

wrong because the two years are simply extremes in the natural variation of 30 nonseeded winters. These examples further illustrate the danger of attempting to conclude anything about a single winter's seeding operation based on this type of target-control analysis.

Figure 4 is a plot very similar to figure 3, but with sites 3 and 8 removed from the calculations. As previously discussed, those sites might have been contaminated by the seeding. Assuming they were affected by seeding in the same direction as the target (presumably increased snowfall), inclusion of sites 3 and 8 might reduce any seeding signal. Figures 3 and 4 are very similar, and the *R*-value is not significantly reduced by excluding sites 3 and 8. The figure 4 data point for the 1993 winter is slightly more above the regression line than in figure 3, with a 12.6-percent (3.7 inches) departure. This departure still falls well within the natural variation from winter to winter.

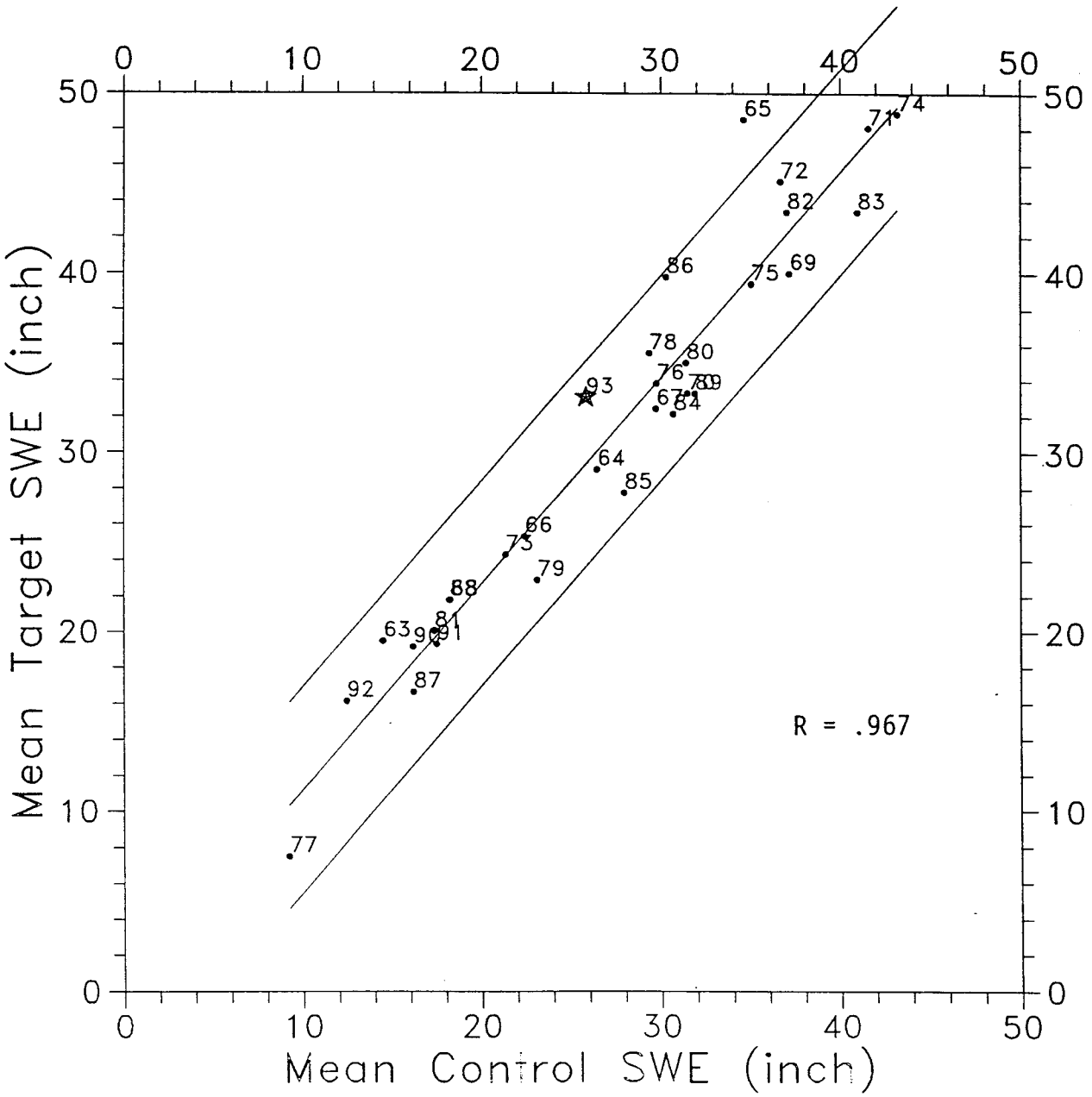

Figure 4. - Similar to figure 3, but without control sites 3 and 8.

Seeding might be expected to have greatest influence at higher, colder elevations. The high temperature dependence of AgI as an effective IN will be discussed later. Consequently, the AgI must typically be transported higher than mountain crest altitudes to encounter SLW (supercooled liquid water) that is cold enough for the AgI to nucleate ice crystals. It can be argued that the resulting "seeded" or artificial ice crystals are more likely to settle on the higher elevation mountains than on valley sites.

In an attempt to "sharpen" the evaluation of the Boise target, the five target sites above 7000 feet were related to the same control sites as in figure 4 because no control sites exist above 7000 feet. The results are plotted on figure 5, which still has a respectable R-value of 0.950. The 1993 data point lies above the regression line by 9.9 percent (3.1 inches), similar to figures 3 and 4. The 1993 departure is less than 1 standard error of estimate from the regression line, therefore well within the natural variation. No evidence exists to show that seeding was more effective at the higher altitude sites.

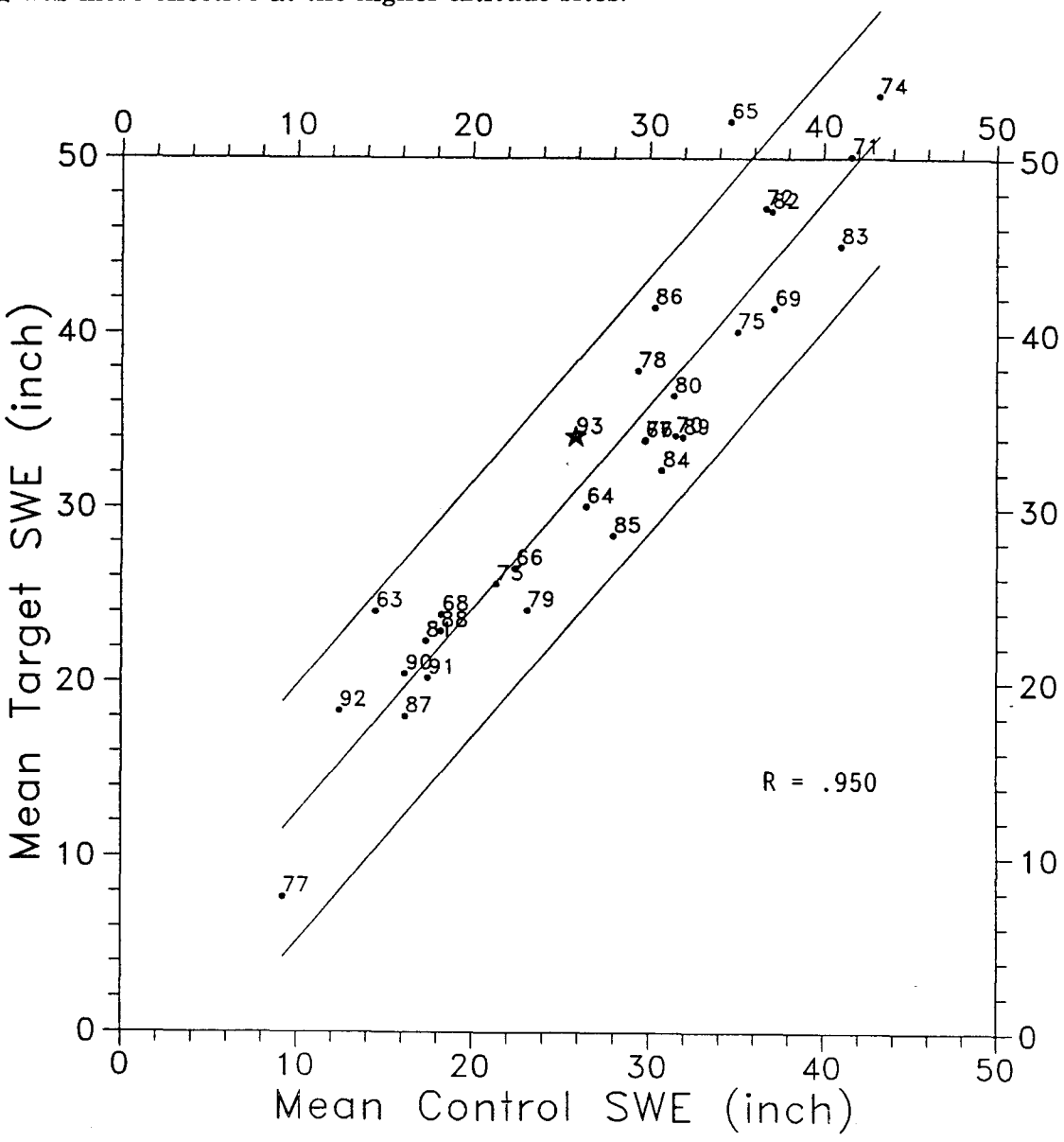

Figure 5. - Similar to figure 4, but for the five Boise target sites above 7000 feet elevation.

Each of the eight target snowpack sampling sites was individually related to the average of the six control sites of table 1, excluding sites 3 and 8. This arrangement was made to test whether some portion of the target area might appear more impacted by seeding than the overall target area. A particular combination of topography, AgI generator siting, etc. might favor some portion of the overall target.

The R-values between the control sites and individual target sites ranged between 0.923 and 0.958, all relatively high values. Departures of the 1993 winter from the regression lines ranged between 8 and 26 percent, the highest value corresponding with a R-value of 0.933. The 1993 data points fell well below 2 standard errors of estimate in each case, and below 1 standard error of estimate in half the cases. Therefore, no statistically significant evidence was provided that seeding increased the 1993 snowpack beyond natural variability at any individual sampling site.

Because seeding did not start until mid-December 1992 in the Boise River drainage, differences between April 1 and January 1 snowpack SWE were examined. Such data would be expected to show more variability than April 1 observations for the entire accumulation season. However, any seeding signal should be less diluted by using the difference data for a period that was entirely seeded.

Although all eight target sites in table 1 had January 1 observations, control sites 4 and 44 did not. Figure 6 is based on the average of control sites 5, 15, 47, and 48. The R-value was not markedly reduced by using the April 1 minus January 1 difference data, resulting in $R = 0.949$. The 1993 observation is well above the estimated value based on the regression line. In fact, it is almost 2 standard errors of estimate above the line. The 1993 measurement represents a 26.7 percent (4.0 inches SWE) increase above the regression line. However, 1965 and 1986 had larger positive departures, and 1972 also had a large departure, so the 1993 observation may represent nothing but a similar natural variation. Nevertheless, the 1993 data point is certainly in the right direction if seeding increased the target area snowfall. The statistical analysis is simply not sensitive enough to determine if seeding was partially responsible for the 1993 positive departures seen in figures 3 through 6. Observations from additional winters are needed to provide more definition.

The four sites immediately downwind from the Boise target, noted in table 1, were compared with control sites 4, 5, 15, 44, 47, and 48. These control sites were all judged unlikely to be contaminated by seeding. These sites are the same control sites used in figures 4 and 5. The resulting R-value was somewhat lower at 0.932, likely because of the greater distance between the downwind and control sites. Figure 7 shows the 1993 data point is slightly less than 1 standard error of estimate above the regression line. The 1993 point represents a 12.7 percent (2.4 inches SWE) positive departure from the estimate provided by the regression line. Although the 1993 data point again has no statistical significance, no indication exists of any downwind decrease in snowfall associated with the seeding.

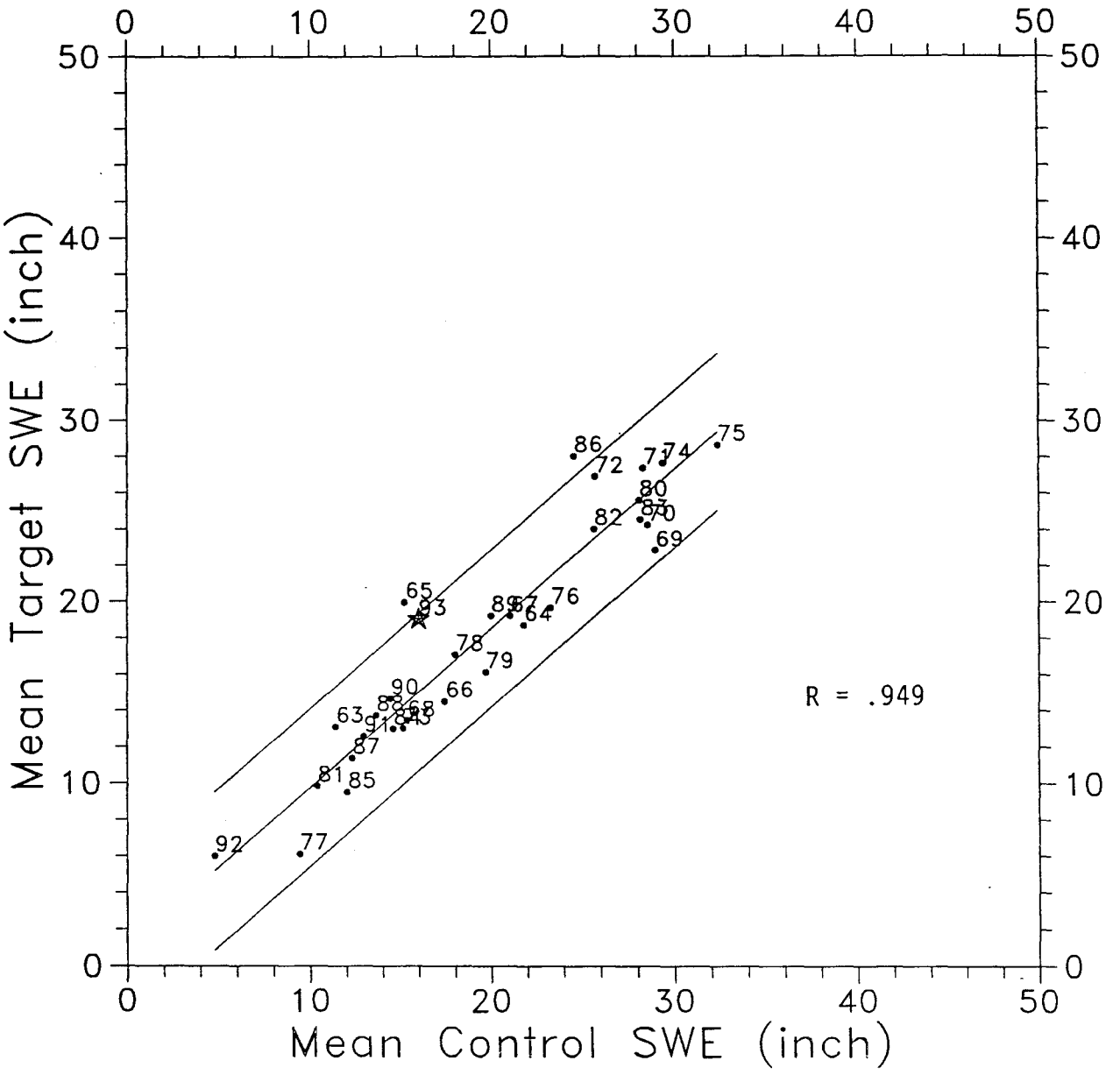

Figure 6. - Plot of average differences between April 1 and January 1 SWE for eight Boise target sites versus four upwind control sites. The straight lines are the linear regression equations and ± two standard errors of estimate for the thirty nonseeded winters.

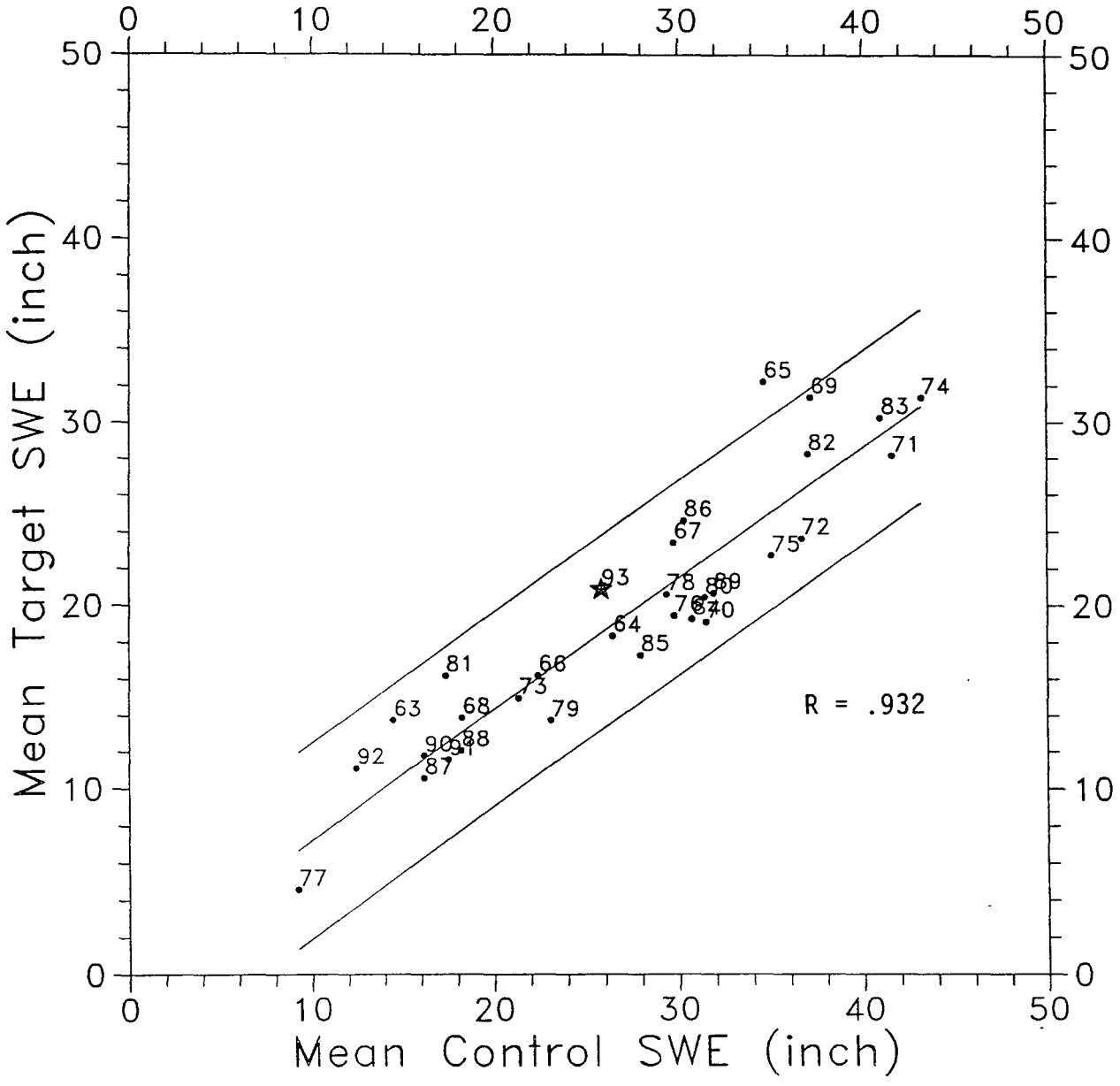

Figure 7. - Similar to figure 3 except average April 1 SWE from four sites downwind of the Boise target versus the average of six upwind control sites.

In conclusion, target-control analysis of the Boise target area was performed using SCS snow course and snow pillow observations. The 1993 winter had somewhat more snowfall in the target than predicted by the 30 prior nonseeded winters. However, the departures were within the range of natural variability. Insufficient information exists to conclude whether the 1993 winter's seeding had any effect on the target area snowfall.

7. EVALUATION OF THE NORTHERN PORTION OF THE UPPER SNAKE

Target Area

The upper Snake project actually had two target areas. One is immediately north and east of the Bear target area, or just downwind from the Bear target for many storms. The other upper Snake target is the region of Idaho immediately west of Yellowstone Park and bordering Montana. The latter area, to be referred to as the "northern upper Snake" target, will be considered first. Both regions and the Bear target area are shown on figure 8. The target areas specified in the NAWC reports are shown. Unlike the boundary around the drainage area of interest shown on figure 2, these target areas appear to coincide with about the 6500-foot elevation contour. Silver iodide generator locations from NAWC maps, and available SCS snow measurements sites above 6000 feet, are also shown on figure 8.

Some of the northern upper Snake target and/or control sites could be contaminated by seeding in the Boise project, the rest of the upper Snake project, and in the Bear project for some wind directions. However, AgI concentrations would be quite diluted that far downwind, which would minimize any impact. Several snow measurement sites exist within 50 miles east of the Boise target which were not chosen for control sites because of concerns about seeding affecting them.

7.1 Control Sites

Table 2 lists the target and control snowpack measurement sites used in evaluation of the upper Snake along the Idaho-Montana border. One of the target sites (No. 60) is just downwind from the target, on the Montana side of the barrier crest. However, the site was included because it was judged more likely to be affected by seeding than the lower elevation sites in Idaho.

As in the Boise target analysis, all available target sites and all available upwind controls sites within reasonable distance were used so long as the measurement sites had good April 1 SWE records since 1963 or earlier, were above 6000 feet elevation, and were judged unlikely to have serious contamination from upwind seeding. No attempt was made at this stage to pick a particular set of target or control sites which might make seeding appear either more or less effective than based on analysis of all available sites in a stated category.

The 14 control sites chosen range from west to northwest of the northern upper Snake target, with several control sites in Montana. Two control sites (Darkhorse Lake and Lemhi Ridge) have co-located snow courses and snow pillows. Both types of measurement were used.

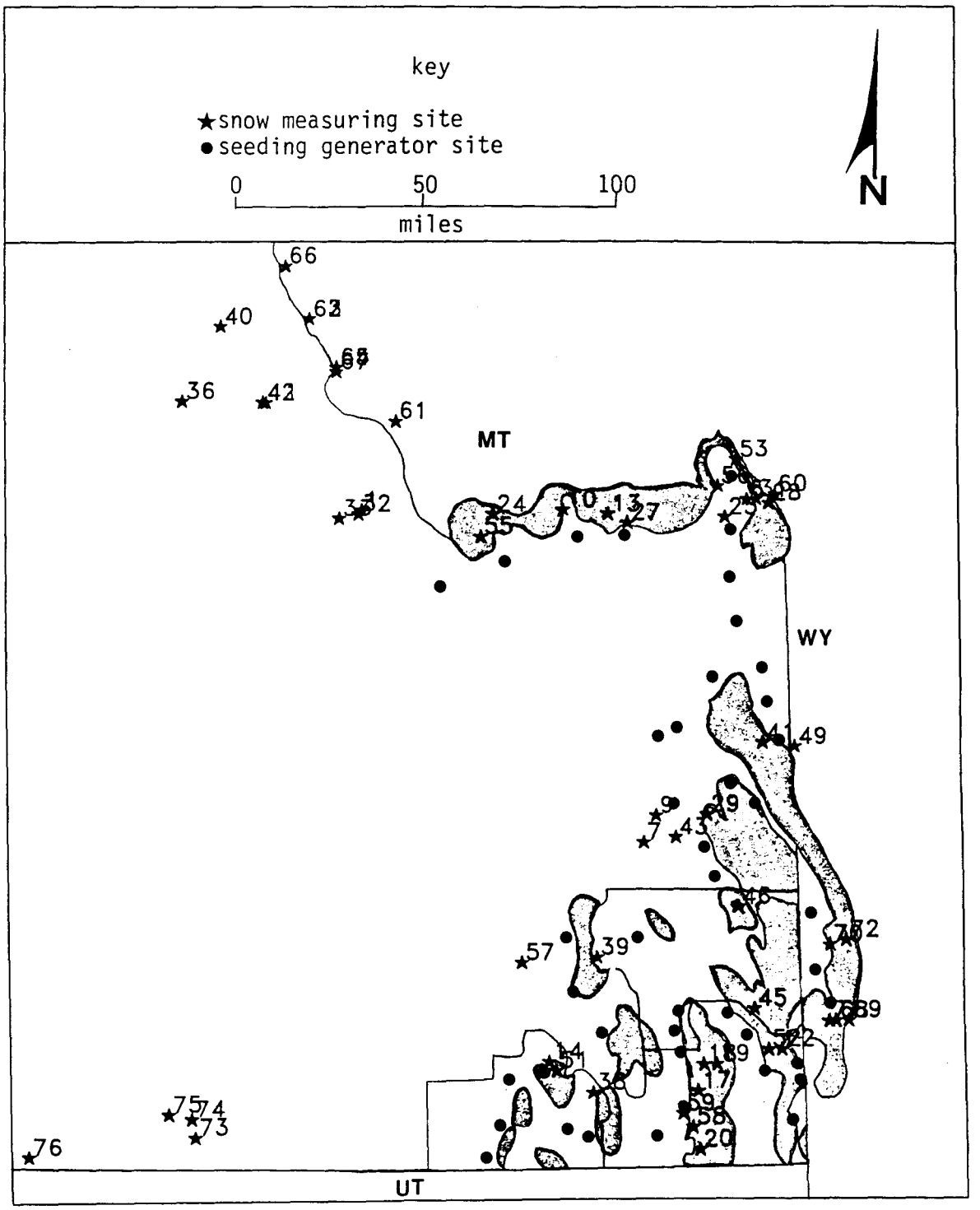

Figure 8. - Map of the upper Snake and Bear target areas showing the locations of AgI seeding generators and snow measurement sites. Numbers by the latter refer to the table 2 and table 4 listings. The NAWC-designated target areas are shaded. The Bear project was in the counties noted in the southeast corner of Idaho.

Table 2. - Listing of SCS snow measurement sites used in analysis of the upper Snake seeding program for target sites along the Idaho-Montana border west of Yellowstone Park and control sites west and northwest of the target.

Site No.	Site Name	SCS I.D.	Elevation (feet)	Latitude (DD-MM)	Longitude (DD-MM)
	(Target Sites)				
6	Big Springs	11E09	6400	44-29	111-16
10	Camp Creek	12E03	6580	44-27	112-14
13	Crab Creek SNOTEL	11E37	6860	44-26	112-00
24	Irving Creek	12E04	7280	44-26	112-36
25	Island Park	11E10	6290	44-25	111-23
27	Kilgore	11E12	6320	44-24	111-54
28	Latham Springs	11E16	7630	44-28	111-09
31	Lucky Dog	11E14	6860	44-29	111-13
53	Valley View	11E08	6680	44-38	111-19
55	Webber Creek	12E05	6700	44-21	112-40
56	White Elephant	11E36	7710	44-32	111-25
60	Black Bear Mountain	11E35	8150	44-30	111-07
	(Control Sites-partial)				
1	Above Gilmore	13E19	8240	44-27	113-18
11	Copes Camp	13E17	7520	44-51	113-49
32	Meadow Lake	13E18	9150	44-26	113-19
33	Moonshine SNOTEL	13E06	7440	44-25	113-25
36	Morgan Creek SNOTEL	14E04	7600	44-51	114-16
40	Perreau Meadows	14D05	8500	45-08	114-04
42	Schwartz Lake	13E16	8540	44-51	113-50
61	Dad Creek Lake Mountain	13E22	8800	44-47	113-07
62	Darkhorse Lake Mountain	13D19	8600	45-10	113-35
63	Darkhorse Lake Pillow	13D19	8700	45-10	113-35
64	Lemhi Ridge Mountain	13E23	8100	44-59	113-26
65	Lemhi Ridge Pillow	13E23	8100	44-59	113-26
66	Slag-a-Melt Lake	13D24	8750	45-22	113-43
67	Trail Creek	13E02	7090	44-58	113-26

7.2 Target-Control Relationships

The first target-control analysis used all 12 target sites and all 14 control sites listed in table 2. A disappointingly low R-value of 0.873 resulted as shown on figure 9. As a consequence of the variability, the target-control relationship has mediocre predictability. Even though the 1993 data point is 28.8 percent (4.2 inches SWE) higher than predicted by the regression line, it is below 2 standard errors of estimate. Three of the 30 nonseeded years on figure 9 had a greater positive departure.

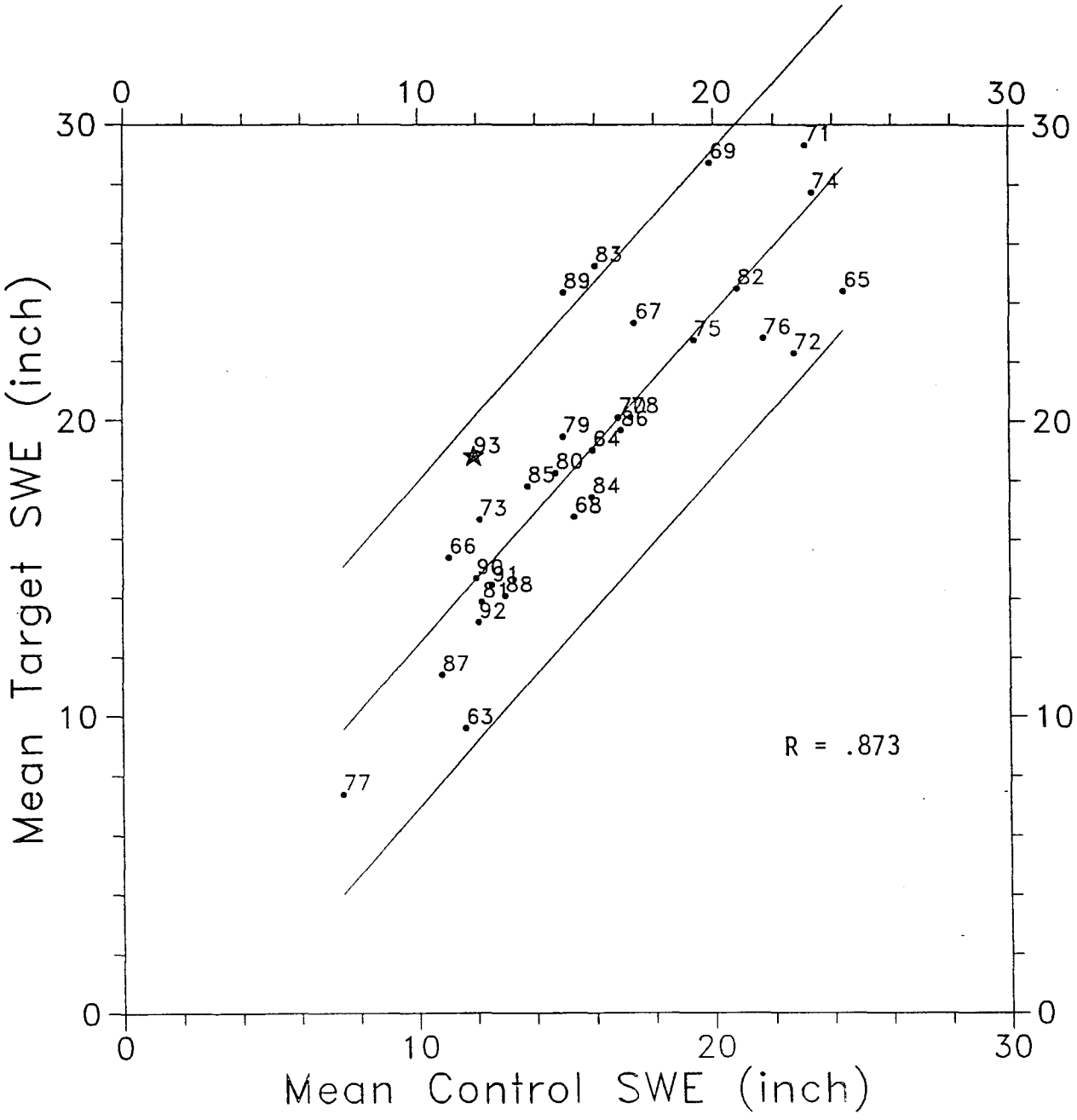

Figure 9. - Similar to figure 3 but for 12 northern upper Snake target sites versus 14 control sites.

An attempt was made to improve the relationship by excluding sites below 7000 feet elevation. All 14 control sites were above 7000 feet, but only 4 target sites were that high. Seeding might be expected to have the greatest effect on these higher target sites. Little improvement in the R-value resulted from this computation, which produced a value of 0.881. Although the plot is not shown, the 1993 data point almost reached 2 standard errors of estimate. One nonseeded year had a higher positive departure, and one had almost as high a departure.

The low correlation coefficients between the target and control sites, and therefore low predictability, are suspected to partially result from the difference in mountain barrier orientation. The axis of the target area mountains is generally east-west; that of the control site barriers is approximately northwest-southeast. Orographic lift, liquid water condensate production, and subsequent snowfall tend to be greatest when winds are almost perpendicular to mountain barriers. Therefore, the target and control areas can be expected to be most affected by different phases of a storm or even by different storms.

A further attempt to improve the degree of association was made by examining R-values between the average of the 9 target sites above 6500 feet and individual control sites. Seeding was expected to have a higher probability of affecting these higher target sites. Each individual control site in tables 1 and 2 was used in these calculations. Individual R-values ranged from 0.67 for the distant site 47 (southwest of Boise) to 0.927 at site 33, west of the target. Surprisingly, four of the five highest values, from 0.876 to 0.900, occurred at control sites northwest of Boise. That region consists of several north-south ridges, dissimilar from the east-west ridge that forms the target area.

It is speculated that the high R-values associated with the distant sites northwest of Boise occurred because that region is similar to the target region for storms tracking from the south to southwest. Few significant mountains exist for such storm tracks for a considerable distance upwind from either the northern upper Snake target or the control area northwest of Boise. In contrast, nearby controls west to northwest of the northern upper Snake target are located downwind from the Boise target, and high mountains east of that target, for south to southwest flow.

Only three sites initially selected as controls for the northern upper Snake, and listed in table 2, had R-values above 0.865. Several of these nearby potential control sites had R-values in the relatively low 0.67 to 0.80 range.

A reasonably high R-value was sought by combining control sites from tables 1 and 2 that had individual R-values exceeding 0.85. The highest value obtained was 0.943 using the four Boise northwest controls (sites 4, 5, 15 and 48), sites 32 and 33 west of the target, and site 36 northwest of the target. The results are shown on figure 10 where the 1993 data point is just above the regression line, equivalent to a 5-percent (1.0-inch SWE) increase. Similar

calculations with the highest individual R-value site, 33, suggested a 3-percent decrease in 1993 snowfall. Calculations with sites 32, 33, and 36 (R = 0.911) suggested a 17-percent increase. But none of these results have statistical significance.

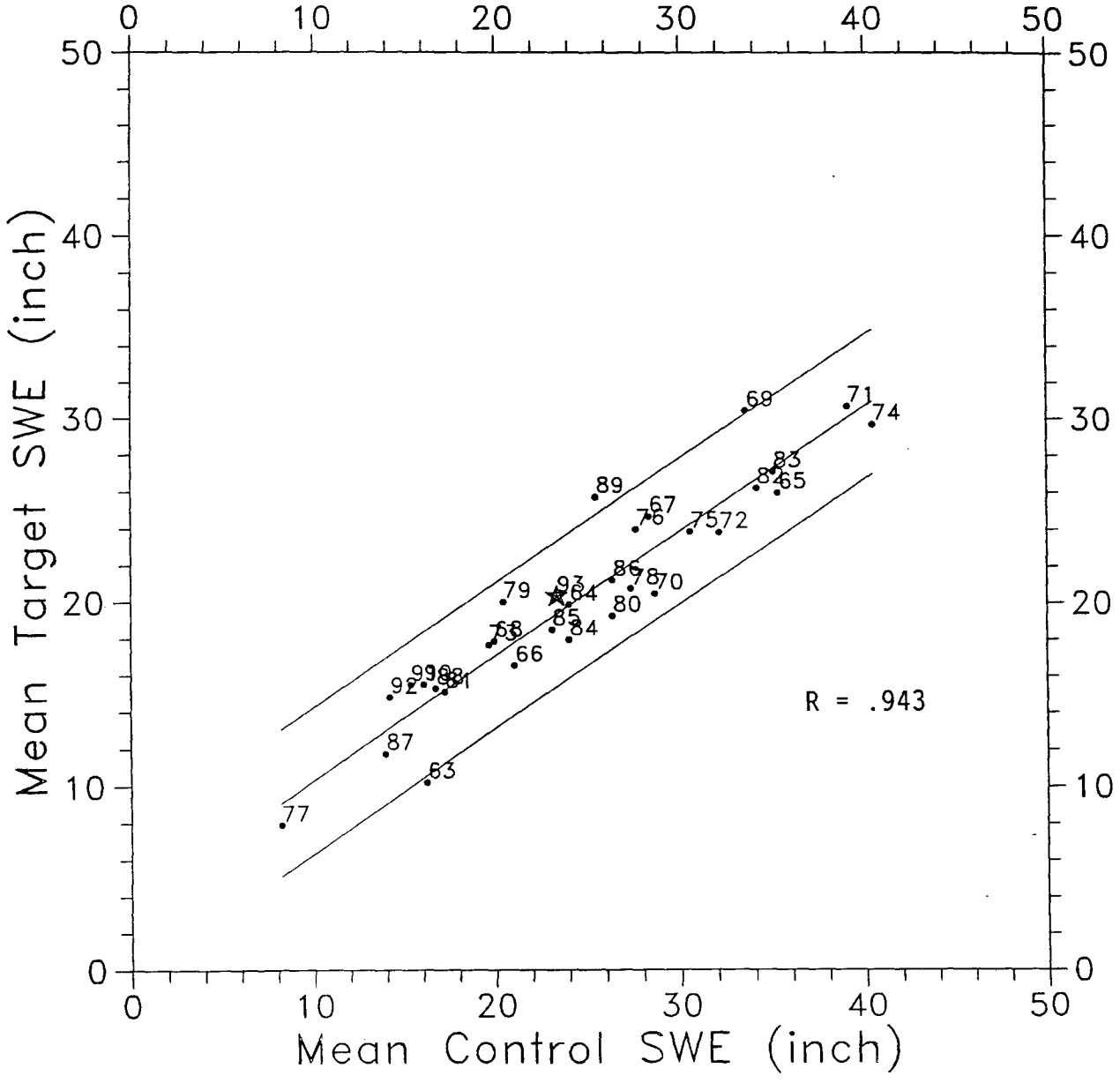

Figure 10. - Similar to figure 9 but for nine northern upper Snake target sites above 6500 feet and seven control sites that individually had R-values of 0.865 or higher with the target.

An attempt was made to use the differences between April 1 and February 1 SWE measurements because the entire seeding generator network in the upper Snake was not operational until about February 1, 1993. Only four of the target sites and five of the control sites shown on figure 8 had the necessary observations. The resulting R-value was a low 0.798. The results indicated that the 1993 data point was 11 percent below the regression line, but the departure had much less than 1 standard error of estimate. Consequently, this attempt produced nothing significant.

One additional analysis was done with this data set to illustrate a point. A search was made for a combination of target and control sites that would make the 1993 seeded winter "look good," regardless of how high or low the degree of association might be or how physically reasonable it was to exclude particular sites. This analysis is not valid, but shows that indiscriminate searching for "good" statistical results sometimes can produce apparently impressive outcomes. Figure 11 shows the highest positive departure obtained for the 1993 data point from many (but not all possible) attempts with various combinations of target and control sites. The 1993 value lies beyond 2 standard errors of estimate; only 1989 has a greater positive departure. One might suggest that the 1993 point is significant at about the 2-percent level, although that suggestion would also be misleading because no randomization was involved.

The target sites used to produce figure 11 are 28, 56, and 60, clustered at the extreme east end of the target area. The control sites are 40, 63, 66, and 67, clustered on the northwest end of the control zone. The target and control sites are about as distant as possible from the selection in table 2. This particular combination of target and control sites probably would not be chosen on any physical basis.

Figure 11 demonstrates that misused statistics can produce misleading results from cloud seeding programs. It would be prudent for cloud seeding sponsors to request the details of any evaluation scheme before a seeding program is initiated. These details should include the specific analysis approaches and the specific data to be used in later statistical analysis.

In summary, the analysis presented provides no evidence that the 1993 cloud seeding in the northern upper Snake target had any significant effect on snowfall. The best target-control relationship that was found, shown as figure 10, suggested no more than a 5-percent increase. However, many nonseeded years had equal and greater departures from the regression equation, and the suggested increase has no statistical significance.

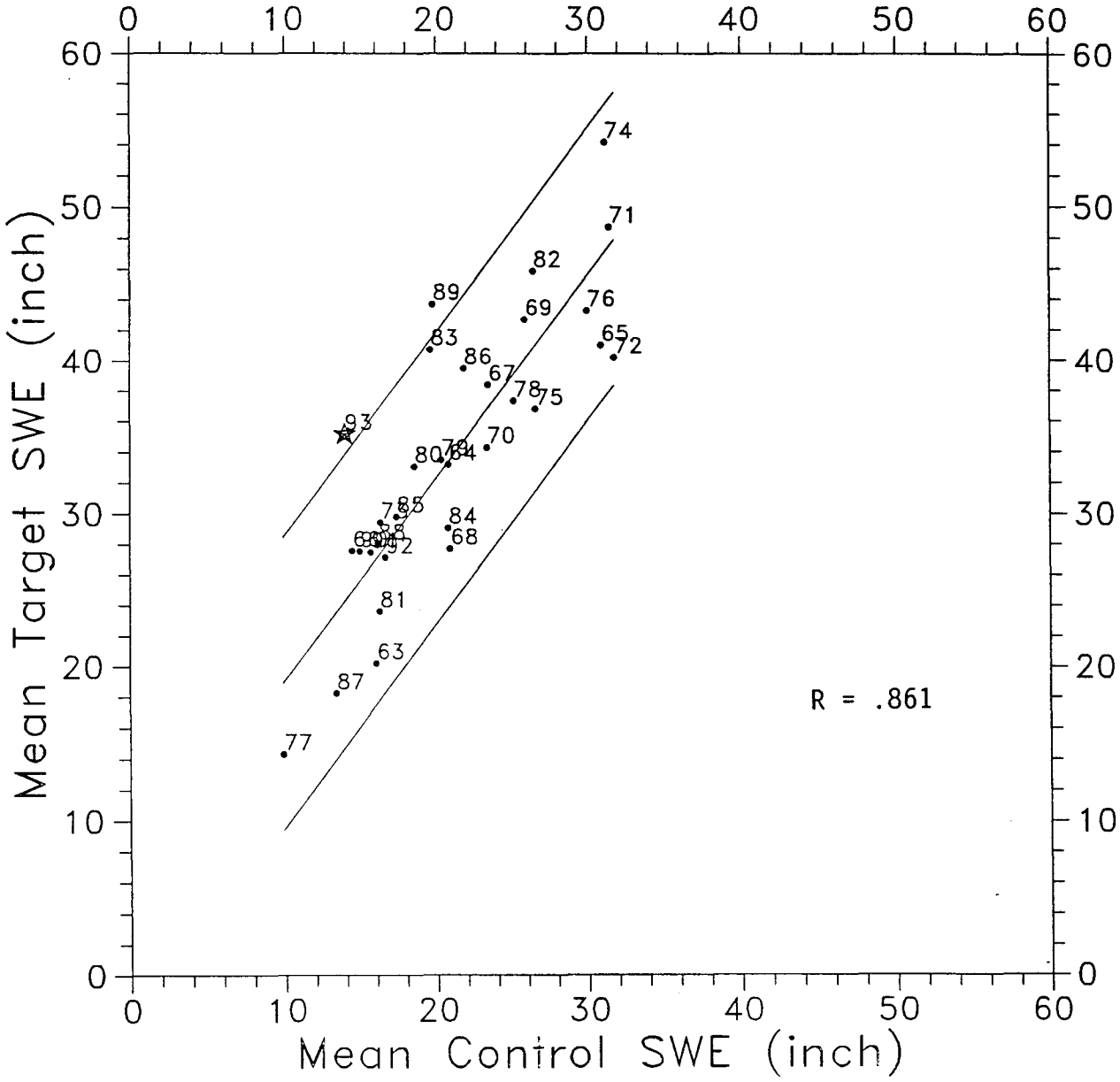

Figure 11. - Plot of average April 1 SWE from three northern upper Snake target sites versus four control sites. This figure illustrates an invalid analysis because the sites were chosen to maximize the 1993 departure from the regression line.

8. EVALUATION OF THE REMAINDER OF THE UPPER SNAKE AND THE BEAR TARGET AREAS

Figure 8 shows the remaining target areas in the upper Snake project and the target areas in the Bear project. The Bear project was located in those counties which form the southeastern corner of Idaho, shown on figure 8. Individual, numbered snow measurement sites and AgI seeding generator locations are plotted on figure 8. The figure shows the minimal physical separation between the Bear and remaining upper Snake targets areas. The Wyoming portion of the upper Snake is immediately downwind from the Bear for westerly flow and therefore may be affected by seeding in the Bear. The upper Snake target areas immediately north of the Bear project may be affected by seeding in the Bear with southerly to southwesterly flow. Accordingly, the entire eastern and southeastern Idaho area and the seeded portion of western Wyoming will be analyzed as one large target area hereafter referred to as "southeast Idaho."

Utah's operational seeding program may affect much of the southeast Idaho target area. Depending upon the winter, two or all three of the Utah counties adjoining Idaho have been seeded in recent years, including the 1993 winter. Some of the AgI released in Utah may be transported into southeastern Idaho with southerly or southwesterly flow. The challenge with this situation is to locate control areas unlikely to be affected by seeding but still highly correlated with target snow measuring sites.

Seeding has not taken place in the Bear River drainage during only 18 winters since 1954-55. The nonseeded winters are listed in table 3 as compiled from Griffith et al. (1983) and Griffith (1993, personal communication).

The scope of this report does not include analyzing the many winters of cloud seeding in the Bear River drainage. Changes in specific target areas and generator locations over time have complicated analysis of this seeding. However, Griffith et al. (1983) presented an evaluation through the 1981-82 winter which suggested that seeding had increased the mountain snowpack.

Table 3. - List of 18 nonseeded winters in the Bear River drainage from 1954-1955 through 1992-1993.

1965-66	1975-76	1984-85
1970-71	1976-77	1985-86
1971-72	1977-78	1986-87
1972-73	1978-79	1987-88
1973-74	1982-83	1990-91
1974-75	1983-84	1991-92

April 1, 1993, SWE observations in the Bear targets and adjoining upper Snake targets have been compared against predictions from target-control relationships for nonseeded winters as previously discussed. The main difference is that the 18 nonseeded winters of table 3 were used to develop the target-control regression equations instead of 30 nonseeded winters as used in previous analyses.

8.1 Control Sites

An extensive search was made for individual control sites that were reasonably well correlated with the southeast Idaho target area, which had 22 snow measurement sites as listed in table 4. Three of the four nearby controls (7, 43, and 57, but not 9) had R-values of 0.85 or higher. Other control sites tested included 73 through 76 near the Idaho-Nevada border, the six control sites of table 1, and eight control sites from table 2 near the west end of the northern upper Snake target.

8.2 Target-Control Relationships

Twelve of the 22 control sites that were tested with the average of the 22 target sites had individual R-values exceeding 0.80. These 12 were sites 4 and 5 northwest of Boise; site 44 southwest of Boise; sites 11, 33, and 65 west of the northern upper Snake target; sites 7, 43, and 57 just north or northwest of the southeast Idaho target area; and sites 73, 74, and 75 well west of the target area. The relationship between the average of these 12 control sites and the 22 target sites is shown on figure 12. The resulting R-value of 0.922 was the highest found of many combinations attempted. Figure 12 shows the 1993 data point was 5.2 percent (0.9 inch) below the value predicted by the regression line calculated for the 18 nonseeded winters. However, the negative departure was not significant.

Control sites 7, 43, and 57 might have been too close to the target to avoid being affected by the seeding. Accordingly, these sites were excluded and the remaining 9 control sites were used with the same 22 target sites. The resulting figure (not shown) and calculations were very similar to figure 12. The R-value degraded slightly to 0.911 and the 1993 data point had a non-significant negative departure of 5.6 percent from the regression line. Another similar calculation was done by excluding control sites 11, 33, and 65, which might have been contaminated by seeding for the Boise target. The remaining six control sites should have been free of any seeding contamination. The R-value for this combination decreased to 0.897 and the 1993 data point had a non-significant negative departure of 6.1 percent. Therefore, calculations excluding possibly contaminated control sites yielded essentially the same results as figure 12.

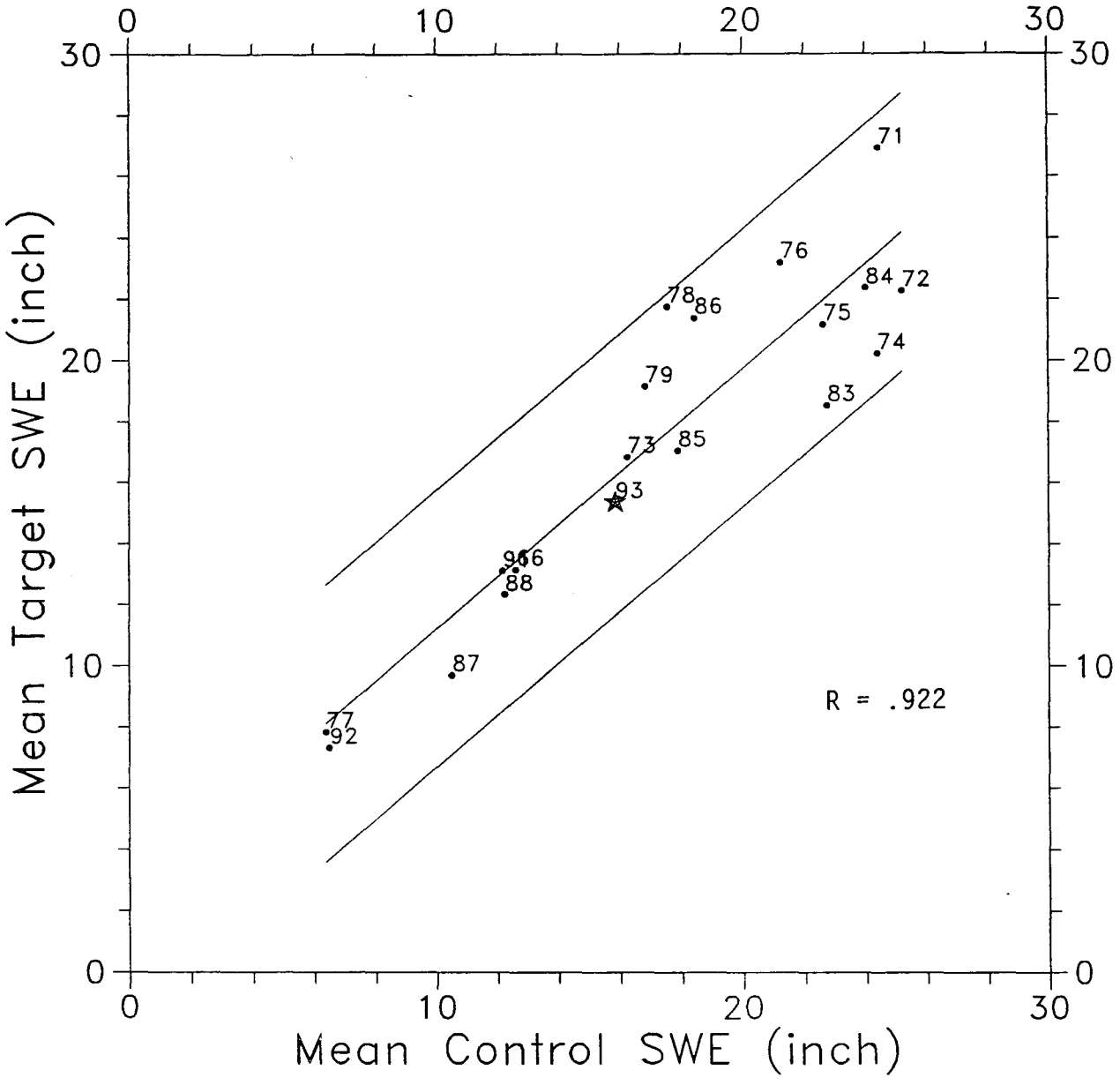

Figure 12. - Similar to figure 10 but for 22 southeast Idaho target sites versus 12 control sites that individually had *R*-values exceeding 0.80 with the target.

Table 4. - Listing of SCS snow measurement sites used in analysis of the southeast Idaho target area.

Site No.	Site Name	SCS I.D.	Elevation (feet)	Latitude (DD-MM)	Longitude (DD-MM)
	(Target Sites)				
14	Daniels Creek	12G12	6270	42-23	112-21
17	Dry Basin	11G14	7820	42-16	111-36
18	Emigrant Summit SNOTEL	11G06	7390	42-22	111-34
19	Emigration Canyon	11G07	6500	42-22	111-30
20	Franklin Basin Pillow	11G32	8170	42-03	111-36
22	Giveout SNOTEL	11G16	6930	42-25	111-10
29	Lava Creek	11F15	7350	43-18	111-31
38	Oxford Spring SNOTEL	12G18	6740	42-16	112-08
39	Pebble Creek	12G02	6400	42-46	112-06
41	Pine Creek Pass	11F02	6720	43-34	111-13
45	Slug Creek Divide SNOTEL	11G05	7225	42-34	111-18
46	Somsen Ranch SNOTEL	11G01	6800	42-57	111-22
49	State Line	11F01	6660	43-33	111-03
51	Upper Elkhorn	12G10	7140	42-21	112-19
52	Upper Home Canyon	11G26	8560	42-25	111-14
58	Willow Flat	11G04	6070	42-08	111-38
59	Worm Creek	11G28	6620	42-11	111-41
68	CCC Camp Wy	10G07	7500	42-31	110-53
69	Cottonwood Creek Pillow	10G25	7600	42-31	110-49
70	Grover Park Divide	10G03	7000	42-48	110-54
71	Salt River Summit Pillow	10G08	7600	42-31	110-55
72	Willow Creek Pillow	10G23	8450	42-49	110-49
	(Control Sites-partial)				
7	Blue Ridge	11F17	6780	43-12	111-51
9	Bone	11F08	6200	43-18	111-47
43	Sheep Mountain SNOTEL	11F11	6570	43-13	111-41
57	Wildhorse Divide SNOTEL	12G17	6490	42-45	112-29
73	Badger Gulch ID	14G03	6660	42-06	114-10
74	Bostetter R.S. SNOTEL ID	14G01	7500	42-10	114-11
75	Magic Mountain SNOTEL ID	14G02	6880	42-11	114-18
76	Wilson Creek ID	15G02	7120	42-01	115-00

Additional attempts were made to search for a seeding effect in portions of the southeast Idaho target area. Any contamination of control site 57 was assumed to be minor compared to any seeding effect at target site 39. The R-value between these nearby sites was a relatively high 0.914. The 1993 data point was again below the regression line, by 11.1 percent in this case, but the departure was less than 1 standard error of estimate.

Similar reasoning led to a comparison of target sites 29, 41, and 49 with control sites 7 and 43. Site 9 was not included as a control site because it decreased the high R-value of 0.963. The results are shown on figure 13 where the 1993 data point is 13.4 percent (1.9 inches) below the predicted value, but less than 2 standard errors of estimate from the regression line.

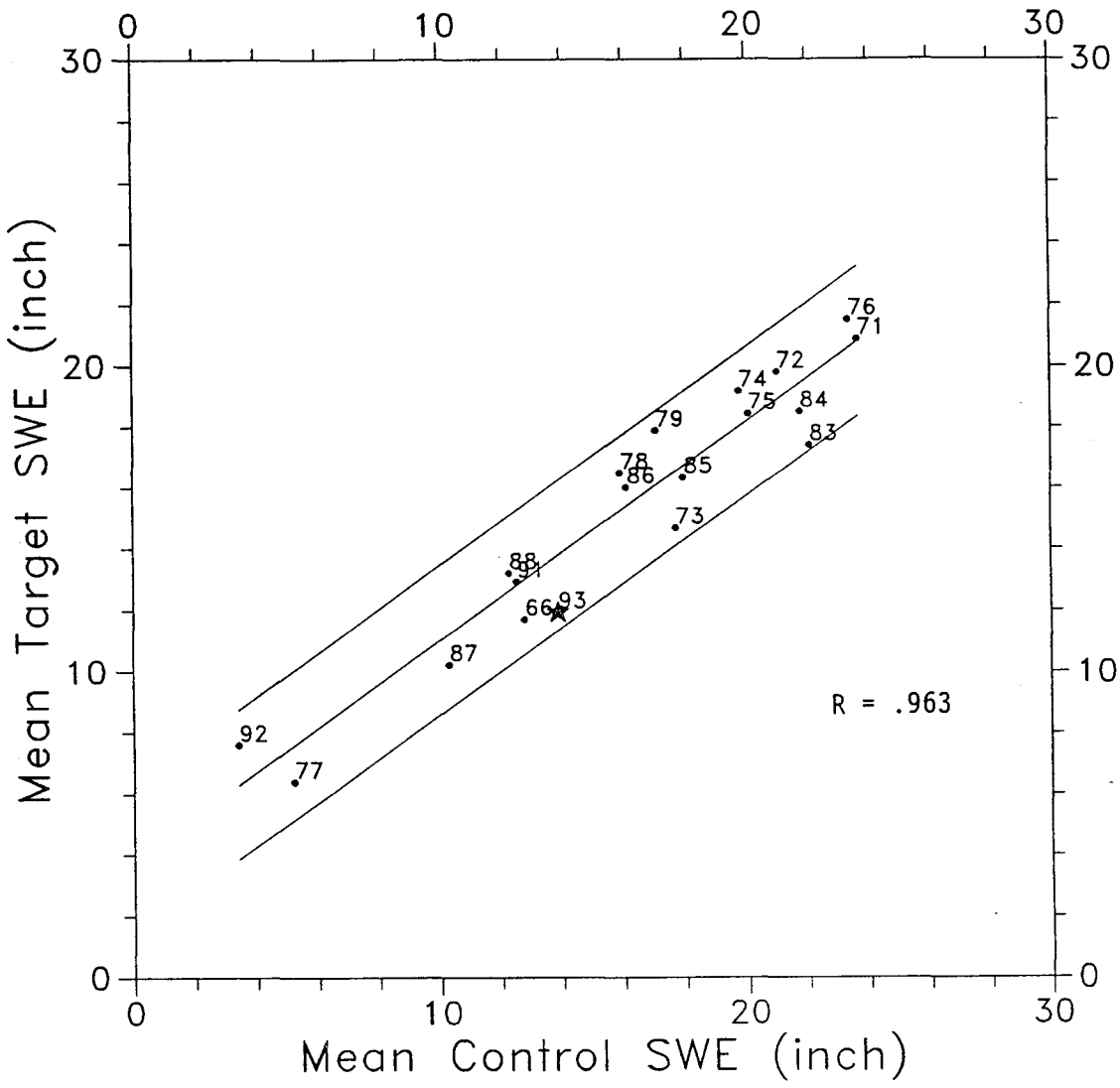

Figure 13. - Similar to figure 12 but for the average of target sites 29, 41, and 49 versus the average of control sites 7 and 43.

In summary, statistical evaluation of the effects of seeding in southeast Idaho revealed no indications of increased snowfall in the target areas. Less snowfall occurred during the seeded 1993 winter than predicted by the 18 previous nonseeded winters, but this result is no more significant than the suggested increases in the other target areas discussed.

9. PHYSICAL EVALUATION OF CLOUD SEEDING EFFECTIVENESS

9.1 Overview of Field Operations and Generator Placement

A Reclamation meteorologist visited the Boise operational area during April 1993. His trip report is attached as appendix B. Briefly, forecasting and operational support for the seeding program were found to be of high calibre. Seeding was initiated by phone calls from NAWC's forecast office in Salt Lake City to locally-hired operators. This approach, although economical, seriously limits possible locations for AgI generator placement. Seeding generators were concentrated at valley bottom locations where roads and phone lines existed and people lived. Such sites are susceptible to low-level trapping inversions and drainage winds which can prevent proper targeting of AgI to cloud levels.

As will be illustrated in the next section, one of the main concerns about the Idaho operational program is the targeting of adequate concentrations of seeding material to cloud levels. Observations from other mountain regions in the West strongly suggest that AgI from the Idaho generators will fail to be transported over mountain barriers during a large fraction of storm periods. Moreover, crosswind distances between seeding generators were often several miles. With such spacing, wide nonseeded regions can expected between AgI plumes when they do reach cloud levels, reducing seeding effectiveness.

9.2 Estimation of the Upper Limit for Snowfall Enhancement

An estimate was made of the upper limit of seeding-caused snowfall production in the Boise target area, hereafter called "upper limit." The Boise target was chosen because it had the longest period of seeding. Moreover, AgI generator density appeared typical of the remainder of the Idaho seeding program.

The upper limit estimate had to be based on a number of uncertain assumptions so the result is necessarily only a crude approximation of reality. It is stressed that each assumption was purposely made in an optimistic sense, so that the resulting upper limit is expected to be higher than seeding could really achieve. The purpose of these calculations was to attempt a "ballpark estimate" of whether it appeared physically reasonably to expect a beneficial snowpack increase from the 1993 Idaho operational cloud seeding.

Suppose that the calculations indicated that it was physically improbable to achieve a seasonal increase on the order of 10 percent as might be anticipated from a successful program (American Meteorological Society, 1992). Such a result was suggested by similar calculations for two Utah target areas reported by Super and Huggins (1992). In that case, interested parties might wish to reconsider the seeding program's design and operation. Conversely, if the calculations suggested that seasonal increases on the order of 10 percent appeared reasonable, program sponsors might be more inclined to continue the program without modification.

Limited physical information exists with which to evaluate most operational seeding programs, and the recent Idaho project is no exception. One reported observation is the total amount of AgI released over the course of the operation. The NAWC monthly reports for the Boise program provide two sets of figures. The per storm totals are based on a generator output of 9 g h^{-1}, but the per month totals are based on 6 g h^{-1}. The higher rate will be used in the following calculations. As will be seen, some of the other assumptions are necessarily so crude that a possible 50-percent error in AgI release rate is of almost minor importance.

The Boise project reportedly released a total of about 24 kg of AgI from all 19 generators during the mid-December to late April period. To convert that quantity of AgI into an upper limit, an estimation of the maximum number of ice crystals that might be produced by the AgI is necessary. Silver iodide particles have the potential to be IN which convert some supercooled liquid (below 0 °C but still liquid) cloud droplets into ice crystals, thereby initiating the snow formation and growth process. Some fraction of the embryonic ice crystals formed by IN may grow to snowflake sizes which settle to the surface as snowfall. Dennis (1980) presents a detailed discussion of this process. The number of IN produced per gram of AgI, called generator effectiveness, depends upon the characteristics of the particular type of generator, the type of seeding solution used and on the wind speed past the generator.

The type of NAWC seeding generators used in Idaho have been calibrated in the Colorado State University Cloud Simulation Laboratory as reported by Griffith et al. (1991). As is typical of ground AgI generators, the NAWC generator effectiveness is about one order of magnitude (a factor of ten) higher with a brisk 20-knot wind past the generator than under light wind speeds of about 5 knots. That increase occurs because the increased dilution with stronger winds reduces the coagulation of the very high concentrations of tiny AgI particles near the generator. Experience at a number of mountain locations has shown that surface winds where valley-floor AgI generators are located are typically light during most winter storms. Accordingly, the light wind AgI generator calibration values will be used in the following calculations. Table 5 lists effectiveness values for the NAWC AgI generator exposed to winds of about 5 knots.

Table 5. - NAWC AgI generator effectiveness values for natural draft conditions observed in the Colorado State University Cloud Simulation Laboratory with a liquid water content of 0.5 g m^{-3} - April 1982.

Cloud temperature (°C)	Ice crystals per gram of AgI
-6	2×10^{10}
-8	2×10^{12}
-10	9×10^{12}
-12	5×10^{13}
-16	5×10^{14}

The main factor determining what fraction of potential IN actually nucleate ice crystals is the SLW temperature reached by the AgI. This determination assumes (1) that SLW is present and (2) that the AgI is transported from ground levels to the SLW zone typically found within 2000 to 3000 feet above the windward slopes and crestline of mountain barriers. Table 5 shows the remarkable increase in effective IN with decreasing temperature that is typical of the particles released by AgI seeding generators. Even higher effectiveness values were measured at colder temperatures. However, observations have shown that winter orographic clouds colder than about -16 °C at the altitudes reached by ground-released AgI are likely to have high natural ice crystal concentrations and little if any SLW. Such cold clouds are unlikely to be suitable for seeding.

The over four orders of magnitude variation in effective IN shown in table 5 provides one of the major uncertainties in estimating how much snowfall can be produced by seeding. For example, if the coldest SLW cloud temperature reached by the AgI is -12 °C instead of -8 °C, the potential exists for the nucleation of 40 times as many ice crystals, all else being equal. Of course, the temperature of the SLW zone varies from storm to storm and even during the course of a storm.

Aircraft tracking of ground-released plumes have indicated that little AgI reaches altitudes higher than 2000 feet above mountain crestlines. Mountain top temperatures during storms with abundant SLW present are estimated to usually be in the range 0 to -12 °C at mountain top elevations typical of the Idaho target areas. This estimate is based on a considerable body of microwave radiometer and/or aircraft observations from Colorado, Montana, and Utah.

Although SLW observations are not available from Idaho mountains, the SCS SNOTEL system has provided reliable measurements of daily snowfall SWE (resolution 0.1 inch) and average temperature (resolution 1 °C) in recent years. These observations were obtained for five sites in the Boise target area and one site immediately east of the target for November through March of each winter from 1984-1985 through 1992-1993. The sites are listed in table 1 as numbers 2, 16, 21, 26, 50, and 54. The nearest reliable average daily temperature measurements for this period were from Bear Canyon, at 7900 feet elevation, about 35 miles east of the Boise target. These observations were used to construct figure 14, which shows the temperature distribution during snowfall events. The lower panel of figure 14 is for all 775 days that had detectable snowfall at two or more of the six observing sites. The upper panel is similar but restricted to the bigger storms, with average precipitation amounts greater than 0.3 inch. According to Super and Huggins (1993), larger snowfall-producing storms tend to have larger amounts of SLW flux. Cloud seeding potential is limited by the amount of SLW flux present among other factors.

Figure 14 shows that almost half (49 percent) of the snowfall days had average temperatures warmer than -6 °C at 7900 feet elevation. The distribution for the larger snowfall days was shifted to warmer temperatures with 66 percent of all days above -6 °C. The temperature was colder than -9 °C on 33 percent of all days and 19 percent of the larger snowfall days.

Examination of Boise target area contour maps revealed that major ridgelines were about 1000 feet higher than the 7900 feet temperature measurement site. In a typical winter orographic cloud, the temperature decreases with altitude at a rate near 0.7 °C per 100 m, equivalent to about 2.0 °C per 1000 feet. Therefore, Boise target area major ridgelines would be about 2 °C colder that the measurements of figure 14. It follows that ridgeline temperatures during winter storms will be above -12 °C during the large majority of cases, and especially during warmer storms with higher amounts of SLW. Ridgeline temperatures will seldom exceed 0 °C. Most significant storm days can be assumed to have ridgeline temperatures between 0 and -12 °C, in agreement with the earlier estimate based on SLW observations in neighboring States.

Assuming that AgI plumes tops are 2000 feet higher and 4 °C colder than the mountain top provides a temperature range of -4 to -16 °C at AgI plume tops. Those storms with more abundant SLW will tend to be on the warmer side of this range. However, AgI effectiveness at -4 °C is insignificant. From table 5, equivalent effectiveness values for temperatures between -6 and -12 °C range between 2×10^{10} to 5×10^{13} ice crystals per gram of AgI, over three orders of magnitude. But plume concentrations decrease with altitude, so only a fraction of all the AgI released is ever exposed to the coldest temperatures at plume top.

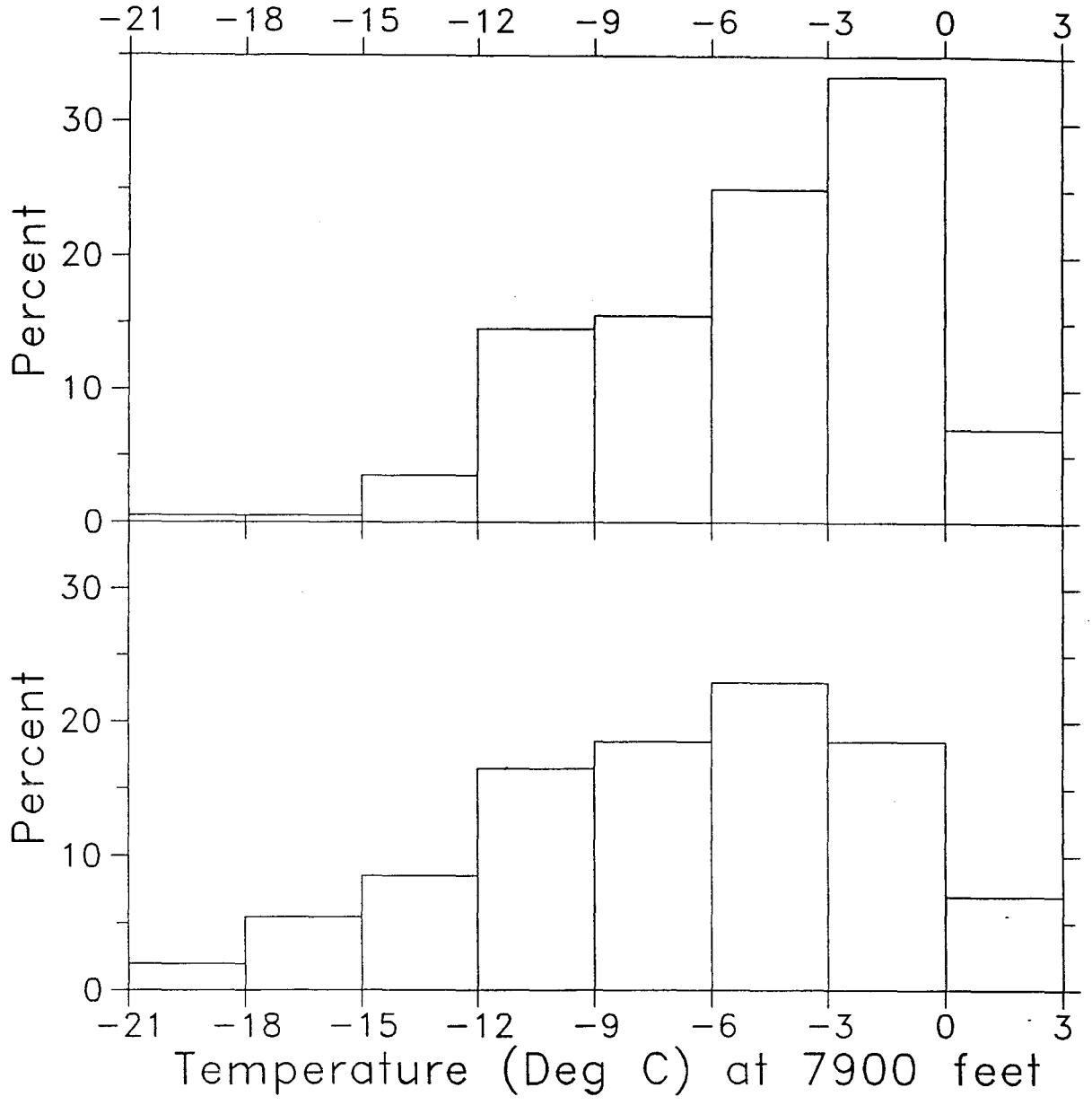

Figure 14. - Frequency distributions of daily snowfall events measured at six SNOTEL sites in and east of the Boise target against the daily average temperature at the 7900-foot elevation Bear Canyon SNOTEL. The upper panel is for 216 days with average SWE above 0.3 inch, and the lower panel is for 775 days with any detectable snowfall at two or more sites.

We will assume that, on average, the AgI reaches SLW cold enough to produce 10^{13} ice crystals per gram of AgI. This number is likely an overestimate because many storms will be warmer than -10 °C in the seeded zone, and many colder storms will be naturally efficient at snowfall production. Because we have assumed that all 24 kg of AgI reached SLW cloud, the resulting number of ice crystals produced is 2.4×10^{17} ice crystals. We will make yet another optimistic assumption that each ice crystal grows and settles to the surface as a snowflake or snow pellet. In reality, an unknown but significant fraction of AgI-nucleated ice crystals sublimate in the descending, warming airflow to the lee of mountain barriers. Moreover, a fraction of any snowflakes initiated by seeding will fall on the downwind side of those mountain crests that form the borders of the drainage basins (e.g., the eastern boundary of the Boise target and the Montana-Idaho border in the northern upper Snake).

Masses of individual ice crystals have been measured by investigators at several mountain locations in the West. Super and Huggins (1992) referred to some of these studies which show that individual ice crystal masses are usually between 0.001 and 0.1 mg. Snow pellets (graupel particles) may have greater masses. Snow pellets grow by the riming process in which very large numbers of cloud droplets are collected and freeze upon an ice particle during its fall. But even densely rimed snow pellets seldom exceed 1 mg and their median masses are about 0.2 mg. Although snow pellets are an important component of many winter storms, most high elevation Idaho snowfall probably accumulates from the numerous hours with snowflakes of limited mass, or aggregates of such snowflakes.

Seeded ice crystals will likely have less mass than the natural ice crystals that have been observed. Natural ice crystals usually originate at high, cold levels in winter orographic clouds and therefore have longer growth times and fall trajectories. For the purpose of calculation, we will assume an average seeded crystal mass of 0.05 mg, which is probably an overestimate. Using this mass with the previously estimated total seasonal production of 2.4×10^{17} ice crystals yields a total snowfall mass of about 10^{13} g, equivalent to 10^{13} cm^3 of water.

The total area of the Boise target shown on figure is roughly 7500 km^2 (7.5×10^{13} cm^2), so the estimated snowfall mass is equivalent to an average water depth over the drainage of about 0.13 cm (0.05 in), a very low amount. The portion of the target area above 7000 feet elevation was planimetered and found to have an area of about 1500 km^2. If the estimated total ice crystal mass was deposited just over that area the resulting water depth would be 0.67 cm (0.26 in). For reference, the 30-year average SWE on April 1 for the five Boise target snow measuring sites above 7000 is 32.4 inches. Therefore, a 10-percent snowfall increase in an average year would be over 3 inches, an order of magnitude higher than the estimated upper limit if <u>all</u> the seeded snow fell above 7000 feet and all within the target.

As discussed by Super and Huggins (1992), IN effectiveness values in winter orographic clouds may be higher than measured in the Colorado State University Cloud Simulation

Laboratory. Conversely, one could argue that IN effectiveness values are lower in natural clouds. For example, tests of the NAWC generator in April 1982 indicated effectiveness values about one order of magnitude higher than shown in table 5 for a cloud liquid water content of 1.5 g m^{-3} in the -10 to -16 °C temperature range. Natural orographic clouds in Idaho can typically have liquid water contents of 0.05 to 0.2 g m^{-3}. Consequently, the values in table 5 may be overestimates for natural clouds. But other differences exist that may affect AgI nucleation of ice crystals, such as marked liquid water spatial gradients and more turbulence in natural clouds. Further investigation of this question is warranted.

Some type of not yet understood ice multiplication process may increase ice crystal concentrations well above the AgI IN concentrations. Aircraft microphysical observations in winter orographic clouds in the intermountain West have suggested that ice multiplication is usually not a major factor in snowfall production. Aircraft measurements in AgI-seeded winter orographic clouds have shown typical ice particle concentrations of 10-20 l^{-1}. Such values do not suggest a significant multiplication process. But ice crystal formation and multiplication processes are not fully understood and are the subject of ongoing research, so the topic remains open. However, in light of current understanding, the Boise operational seeding program did not likely provide enough IN to markedly increase the seasonal snowfall.

Other constraints on seeding effectiveness were ignored in the above calculations but should be recognized. Recent reviews of winter orographic cloud seeding by Reynolds (1988) and Super (1990) discuss the constraints more fully. One constraint is the trapping of the valley-released plumes because of atmospheric stability and associated light and variable surface winds. Weather modification studies have produced an increasing realization of the difficulty in achieving proper targeting of ground-released AgI into winter orographic clouds. Conditions have been observed to be unfavorable for vertical transport of valley-released AgI to cloud levels during portions of many winter storms. The frequency with which the Idaho operational seeding resulted in AgI transport to SLW levels above the mountains is not known. This known problem was ignored in the above calculation, which assumed that all released AgI reached cloud levels.

Observations in neighboring States have indicated that SLW, the necessary "raw material" needed for seeding effectiveness, is present during only a fraction of the storm episodes. Consequently, seeding must be ineffective some portion of the time that the AgI does reach cloud levels. This factor was also ignored, and it was assumed that SLW was always present and that the AgI always nucleated ice crystals.

In view of the number of optimistic assumptions made in estimating an upper limit, the resulting low snowfall amounts are particularly discouraging. They strongly suggest that the Boise operational seeding program likely had only a limited impact on seasonal snowpack accumulation.

A further check was made on the estimated upper limit by making similar calculations for the BRE (Bridger Range Experiment), conducted in southwestern Montana in the early 1970's. This randomized experiment, reported by Super and Heimbach (1983), took place in mountainous terrain and a climatic regime similar to the Boise target area. The BRE provided strong statistical suggestions that about a 15-percent seasonal snowfall increase could be achieved if all storm days were seeded. Because the BRE was randomized, only about half the experimental days were seeded, so the equivalent increase is 7.5 percent of the total experimental day snowfall. The seasonal increase would be somewhat less because additional snow occurred on days set aside for special experiments and on "blown" forecast days.

If the BRE results are assumed to be valid, a maximum snowfall production estimate similar to that done for the Boise target should provide a higher value. Otherwise, either the BRE results are suspect or the approach used to estimate the upper limit is flawed and should be reexamined.

The same assumptions made for the Boise target were made for the BRE, which used high altitude AgI generators on the windward slope of a north-south mountain ridge to affect the next ridge downwind. The intended target area was small (218 km^2 above the 6000 feet contour) and only two generators were used, each releasing AgI at the rate of 30 g h^{-1}. The total AgI released during the two-winter BRE was over 108 kg, or an average of 54 kg per winter, even though over half the storm days were left unseeded. For comparison, the entire 1993 winter release for the Boise target was 24 kg from 19 generators.

The AgI generators used in the BRE were calibrated in the same Cloud Simulation Laboratory as the NAWC generators, but much earlier in May 1972. The BRE generator effectiveness was tested only at 1.5 g m^{-3} cloud liquid water and was found to be higher than the values for the NAWC generator given in table 5 for 0.5 g m^{-3}. Values for natural draft (about 5 knots) flow past the BRE generator were 6×10^{13} ice crystals per gram of AgI at -10 °C and 3.5×10^{14} at -12 °C. These values are about seven times higher than those of table 5.

The higher values for the BRE generator may have occurred chiefly because it was tested under a higher liquid water content. As mentioned earlier, the NAWC generator had about one order of magnitude higher values at 1.5 g m^{-3}, which would make it comparable to the BRE generator. But technical improvements in the Cloud Simulation Laboratory over the years have modified test results to further complicate comparison of these different types of AgI generators tested several years apart. For example, the same type of NAWC generator was tested in October 1978. These tests, done at 1.5 g m^{-3}, indicated lower effectiveness values than the 1982 tests at temperatures below -10 °C. The older 1978 values were less than half the 1982 values below -12 °C. In view of these uncertainties, the BRE AgI

generator effectiveness will be assumed identical to the NAWC generator results given in table 5.

Multiplying 54 kg of AgI by 1 X 10^{13} IN g^{-1} provides an estimate of 5.4 X 10^{17} effective IN per winter for the BRE. If each IN created a snowflake of average mass 0.05 mg as assumed in the Boise calculations, the resulting total mass would be 2.7 X 10^{13} g, equivalent to a liquid water volume of 2.7 X 10^{13} cm^3. Analysis by Super and Heimbach (1983) suggested most of the BRE seeding effect occurred over an approximately 300 km^2 area called Zone 1. If the calculated water mass was deposited uniformly over 300 km^2 (3 X 10^{12} cm^2), the resulting water depth would be 9 cm (3.5 inch). For comparison, the average snowfall on all experimental days was calculated for the 12 gauges in Zone 1. A similar value of just over 10 inches resulted for both BRE winters. A 7.5-percent seeding-caused increase, if real, would be about 0.75 inch, or 21 percent of the estimated upper limit.

The estimated BRE upper limit is over an order of magnitude higher than the Boise upper limit estimated for the assumption that the entire seeding effect was above 7000 feet (3.5 inches versus 0.26 inches). The difference is even greater if the presumed Boise seeding effect occurred over a larger fraction of the entire target area. The main difference in the Boise and BRE calculations is that the BRE released more AgI attempting to affect a much smaller target area. The BRE target area was only 20 percent of the Boise target area above 7000 feet elevation, and only about 4 percent of the total Boise target shown on figure 2.

The calculations suggest that a seasonal snowpack increase of about 7.5 percent for experimental day snowfall may be physically reasonable for the amount of seeding that was done during the BRE. The calculations do not suggest it is physically reasonable to expect a similar increase for the Boise target area in 1993.

Similar calculations were not done for the other two Idaho seeding projects which appear to have target areas at least as large as the Boise project. A brief review of their seeding operations suggests results of such calculations would be no more encouraging. Fifteen storms were seeded in the upper Snake project, and about 28 kg of AgI was released from the network of 25 generators. An average of 13.5 generators was used per storm. Nine storms were seeded in the Bear project, where 15 kg of AgI was released from the network of 18 generators. An average of 11.8 generators was used per storm in the Bear program.

10. CONCLUSIONS AND RECOMMENDATIONS

Several target-control comparisons were made for the 1993 Idaho operational cloud seeding program. These analyses provided no convincing statistical evidence that the program succeeded in its goal of enhancing the mountain snowpack to any beneficial extent. However, this statistical analysis approach cannot discern a limited increase from a single winter's

seeding. Several winters with consistent increases above predicted seasonal SWE amounts would be needed to strongly suggest that seeding was successful. Such a suggestion would not constitute scientific proof, but might satisfy many interested parties that seeding was an economic risk worth taking.

A change in total 1993 seasonal snowpack accumulation of approximately 10 percent, either an increase or decrease, would not be discernable from the target-control approach or any other known statistical analysis approach. Figure 3 provides a good example of the problem. The 1993 winter's SWE in the Boise target was about 10 percent higher than predicted by the 30 preceding nonseeded winters, and the correlation coefficient between target and control areas was a high 0.971. Nevertheless, the 1993 data point was well within natural winter-to-winter variability.

Several target-control comparisons showed that the 1993 seeded winter had somewhat more snowfall than predicted in the Boise and northern upper Snake targets. Similar comparisons showed that the 1993 winter had somewhat less snowfall than predicted in the remainder of the upper Snake and in the Bear targets (considered together as southeast Idaho). However, none of these results have any statistical significance. In other words, the apparent increases and decreases may well have been caused by natural variability, and any limited seeding effect was "lost" in the "noise."

An approximate upper limit of snowfall production caused by seeding was estimated by physical reasoning for the Boise target area. The estimate was based on a number of optimistic assumptions, which should lead to a higher upper limit than physically possible to achieve. The upper limit was only 0.05 inches additional precipitation if applied uniformly to the entire Boise target area, or 0.27 inches if applied to that part of the area above 7000 feet elevation. This result is not encouraging. When the same set of assumptions was applied to a past seeding experiment in southwestern Montana, the upper limit was over 3.5 inches, primarily because more AgI was released to affect a much smaller area.

The estimates of maximum possible snowfall production are admittedly crude. One of the major uncertainties is how effective AgI is in producing IN in winter orographic clouds as opposed to laboratory clouds. Another major uncertainty in the Boise calculations is the targeting of SLW clouds with valley-released AgI (observations not discussed here demonstrated that routine targeting was achieved with high altitude generators in the southwestern Montana experiment). In spite of the uncertainties in the assumptions and estimates presented, the best current physical understanding strongly suggests that operational seeding of the type conducted in the Boise project is unlikely to produce more than minor snowfall increases. The AgI IN production rates appear to be lower than desired for effective snowfall augmentation.

It is recommended that the Idaho operational seeding design be reconsidered and modified to significantly increase IN production. A relatively simple and economical improvement would be to retrofit AgI generators with ventilating fans to decrease coagulation losses. Because most generators are operated near homes or businesses, electrical power should be available. Such a modification should increase IN output from the same quantity of AgI by up to an order of magnitude at locations which experience light winds during storms.

It is recommended that consideration be given to increasing the density of seeding generators. The 1993 configuration typically had crosswind distances of several miles between generators. In some cases, generators were over 10 miles apart. Evidence from both observations and numerical model results indicates that seeding plume widths will generally be a fraction of these typical crosswind spacings. As a consequence, wide unseeded regions can be expected to exist between seeding plumes, decreasing seeding effectiveness.

The use of valley generators raises serious concerns about targeting in a large fraction of storm periods. Recent investigations in Utah, where similar valley seeding was conducted, have shown vertical transport of the AgI to SLW cloud levels when embedded convection was present, although AgI concentrations were low (Heimbach and Super, 1992). However, many Utah winter storm periods did not have embedded convection, but did have strong atmospheric stability above valley floors. A stable lower atmosphere impedes or completely prevents vertical transport of valley-released AgI to cloud altitudes. The frequency of atmospheric stability can be expected to increase northward from Utah to Idaho. For example, the large majority of radiosonde observations taken during winter storms in southwestern Montana during the BRE indicated a stable atmosphere.

It is recommended that future attention be given to the AgI targeting problem. As a minimum, snow samples could be collected in the targets for analysis of silver-in-snow concentrations. This technology can at least indicate whether the seeding material reaches the target. Finding enhanced silver levels does not prove that seeding produced more snowfall because scavenging by natural snow could bring some or all of the AgI to the surface. However, failure to find increased silver in target areas should raise concerns about where the seeding material is actually going.

Another recommended approach to investigating the targeting problem is to use numerical models to predict seeding plume behavior under a variety of atmospheric conditions. Some models have evolved to the point that they provide reasonable simulations. Although some uncertainty remains, model simulations are relatively inexpensive compared to observational programs, and model simulations can provide a reasonable first approximation to reality. Their use is a far better approach to testing the effectiveness of a particular seeding generator network than simply "guessing and hoping."

It is recommended that consideration be given to using remote-controlled seeding devices in future operations in Idaho. Such devices are more expensive than manual generators. However, they can be located at sites from which routine targeting of SLW clouds can be expected, such as on the windward slopes of mountain barriers. Several investigations have demonstrated the effectiveness of high altitude ground-based seeding in actually seeding the clouds with appropriate AgI concentrations. The same cannot be said for valley ground-based seeding.

It is recommended that consideration be given to using seeding agents that have more warm temperature effectiveness. Although "silver iodide" is used as a generic term, a number of different solutions have been developed, combining AgI with other chemicals, which appear to nucleate more ice crystals at relatively warm temperatures than the seeding solution used in Idaho.

Another approach to overcoming the problem of creating adequate ice crystal concentrations at SLW temperatures warmer than about -8 °C is to seed with propane. Reynolds (1991) discusses this experimental approach currently being tested by the State of California. Ice crystals can be created by expansion of the propane, which cools the nearby cloudy air to temperatures well below -40 °C. Propane seeding can create high concentrations of ice crystals at temperatures just below 0 °C. Propane dispensers are simple, much less expensive than remote-controlled AgI generators, and quite reliable. It is recommended that remote-controlled, high elevation propane dispensers be considered as part of the seeding strategy for future Idaho operations.

Finally, it is recommended that if future statistical analysis of operational seeding is undertaken in Idaho, the procedures and target and control sites be chosen and documented before seeding commences. Moreover, to further minimize bias, such analysis should be undertaken by independent, disinterested parties such as University scientists.

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APPENDIX A

Listing of all target and control snow measurement sites used in analysis of the 1992-1993 Idaho cloud seeding program

Site No.	Snow Measurement Site Name	SCS I.D.	Elevation (feet)	Latitude (DD-MM)	Longitude (DD-MM)
1	Above Gilmore	13E19	8240	44-27	113-18
2	Atlanta Summit SNOTEL	15F04	7580	43-45	115-14
3	Banner Summit SNOTEL	15E11	7040	44-18	115-14
4	Bear Saddle SNOTEL	16E10	6180	44-36	116-58
5	Big Creek Summit Pillow	15E02	6580	44-38	115-48
6	Big Springs	11E09	6400	44-29	111-16
7	Blue Ridge	11F17	6780	43-12	111-51
8	Bogus Basin	16F02	6340	43-46	116-06
9	Bone	11F08	6200	43-18	111-47
10	Camp Creek	12E03	6580	44-27	112-14
11	Copes Camp	13E17	7520	44-51	113-49
12	Couch Summit No. 2	14F18	6840	43-31	114-48
13	Crab Creek SNOTEL	11E37	6860	44-26	112-00
14	Daniels Creek	12G12	6270	42-23	112-21
15	Deadwood Summit SNOTEL	15E04	6860	44-33	115-34
16	Dollarhide Summit SNOTEL	14F08	8420	43-36	114-40
17	Dry Basin	11G14	7820	42-16	111-36
18	Emigrant Summit SNOTEL	11G06	7390	42-22	111-34
19	Emigration Canyon	11G07	6500	42-22	111-30
20	Franklin Basin Pillow	11G32	8170	42-03	111-36
21	Galena Summit SNOTEL	14F12	8780	43-51	114-43
22	Giveout SNOTEL	11G16	6930	42-25	111-10
23	Graham Ranch	14F05	6270	43-47	114-25
24	Irving Creek	12E04	7280	44-26	112-36
25	Island Park	11E10	6290	44-25	111-23
26	Jackson Peak SNOTEL	15E09	7070	44-03	115-27
27	Kilgore	11E12	6320	44-24	111-54
28	Latham Springs	11E16	7630	44-28	111-09
29	Lava Creek	11F15	7350	43-18	111-31
30	Lost-Wood Divide Pillow	14F03	7900	43-50	114-16
31	Lucky Dog	11E14	6860	44-29	111-13

APPENDIX A — Continued

32	Meadow Lake	13E18	9150	44-26	113-19
33	Moonshine SNOTEL	13E06	7440	44-25	113-25
34	Moores Creek Summit	15F01	6100	43-55	115-40
35	Moores Creek Summit SNOTEL	15F01	6100	43-55	115-40
36	Morgan Creek SNOTEL	14E04	7600	44-51	114-16
37	Mount Baldy	14F09	8920	43-40	114-24
38	Oxford Spring SNOTEL	12G18	6740	42-16	112-08
39	Pebble Creek	12G02	6400	42-46	112-06
40	Perreau Meadows	14D05	8500	45-08	114-04
41	Pine Creek Pass	11F02	6720	43-34	111-13
42	Schwartz Lake	13E16	8540	44-51	113-50
43	Sheep Mountain SNOTEL	11F11	6570	43-13	111-41
44	Silver City	16F03	6400	43-00	116-44
45	Slug Creek Divide SNOTEL	11G05	7225	42-34	111-18
46	Somsen Ranch SNOTEL	11G01	6800	42-57	111-22
47	South Mountain Pillow	16G01	6500	42-46	116-54
48	Squaw Flat Pillow	16E05	6240	44-46	116-15
49	State Line	11F01	6660	43-33	111-03
50	Trinity Mountain SNOTEL	15F05	7770	43-38	115-26
51	Upper Elkhorn	12G10	7140	42-21	112-19
52	Upper Home Canyon	11G26	8560	42-25	111-14
53	Valley View	11E08	6680	44-38	111-19
54	Vienna Mine Pillow	14F04	8960	43-48	114-51
55	Webber Creek	12E05	6700	44-21	112-40
56	White Elephant SNOTEL	11E36	7710	44-32	111-25
57	Wildhorse Divide SNOTEL	12G17	6490	42-45	112-29
58	Willow Flat, ID	11G04	6070	42-08	111-38
59	Worm Creek, ID	11G28	6620	42-11	111-41
60	Black Bear, MT	11E35	8150	44-30	111-07
61	Dad Creek Lake, MT	13E22	8800	44-47	113-07
62	Darkhorse Lake, MT	13D19	8600	45-10	113-35
63	Darkhorse Lake Pillow, MT	13D19	8700	45-10	113-35
64	Lemhi Ridge, MT	13E23	8100	44-59	113-26
65	Lemhi Ridge Pillow, MT	13E23	8100	44-59	113-26
66	Slag-A-Melt Lake, MT	13D24	8750	45-22	113-43
67	Trail Creek, MT	13E02	7090	44-58	113-26

APPENDIX A — Continued

68	CCC Camp, WY	10G07	7500	42-31	110-53
69	Cottonwood Creek Pillow, WY	10G25	7600	42-31	110-49
70	Grover Park Divide, WY	10G03	7000	42-48	110-54
71	Salt River Summit Pillow, WY	10G08	7600	42-31	110-55
72	Willow Creek Pillow, WY	10G23	8450	42-49	110-49
73	Badger Gulch, ID	14G03	6660	42-06	114-10
74	Bostetter R.S. SNOTEL, ID	14G01	7500	42-10	114-11
75	Magic Mountain SNOTEL, ID	14G02	6880	42-11	114-18
76	Wilson Creek, ID	15G02	7120	42-01	115-00

APPENDIX B

Boise Area Trip Report
by Jack McPartland

A site inspection visit to the Boise area was conducted during the period April 20-22, 1993. Analysis techniques selected for program evaluation, data to be used, and some preliminary statistical results were discussed with the Idaho Department of Water Resources and Reclamation Pacific Northwest Regional Office personnel during an April 20 meeting. The analysis approach was acceptable to both State and Federal representatives.

An informational meeting was held April 21 with Mr. Paul Deveau, Assistant Project Manager for the Boise Project Board of Control. Mr. Deveau was very satisfied with the NAWC equipment, support and operation of the program. NAWC provided an on-site technician to maintain and resupply the generators, and made seeding start and stop decisions from their weather center in Salt Lake City. Seeding was initiated and terminated through phone calls by NAWC to the contract generator operators. The entire seeding project was initiated in a very short time frame, and Mr. Deveau pointed out that as a result some compromises in generator spacing and their physical locations in relation to terrain were necessary. For example, some areas in which it might have been desirable to locate generators either did not have telephone service available or were uninhabited. Therefore, generators were generally placed in relatively low elevation, valley bottom locations. Targeting of the seeding material from such placements may be seriously hindered by trapping inversions. Moreover, drainage winds can also preclude transport of the seeding material to the target clouds in the time-frame and/or concentration anticipated. Possible program improvements, perhaps utilizing remote-controlled generators, were discussed.

Following the meeting with Mr. Deveau, a representative generator site at Idaho City was visited. The generator operator, Mr. Campbell, was very complimentary of the NAWC equipment, support and seeding decision process. He experienced some initial problems with fluctuating solution flow rates in the generator at his site, but this problem was quickly rectified by NAWC. After the repairs, the flow rate was essentially constant with time and seldom required any flow meter adjustment. This gives confidence that the generators were operating at their desired output throughout seeding periods. It was noted by Mr. Campbell that the weather forecasting accuracy for the initiation of seeding events was exceptional. He felt strongly that no storm periods were missed due to inaccuracies in forecasts. He also noted that the winds at the generator location were almost always calm during seeding periods. This is somewhat disturbing, as it can imply that transport of the seeding material from the ground to the clouds may not have occurred efficiently. No local wind data are available to address this issue, and future implementation of a wind measuring network would aid in project evaluation efforts.