Results Obtained from Regression Equations Developed for the Operational Upper Snake River Cloud Seeding Program

Prepared for

High Country Resource Conservation and Development Council
Idaho Water Resource Board

by

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Summary of Regression Equation Development and Evaluation of the Operational Upper Snake River Cloud Seeding Program (Task 10)

by

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Background

One commonly employed statistical technique that has been utilized in the evaluation of operational cloud seeding programs is the "target" and "control" comparison. This technique is described by Dr. Arnett Dennis in his book entitled "Weather Modification by Cloud Seeding (1980)". This technique is based on the selection of a variable that would be affected by seeding (e.g., liquid precipitation, snowpack or streamflow). Records of the variable to be tested are acquired for an historical (not seeded) period of many years duration (20 years or more if possible). These records are partitioned into those located within the designated "target" area of the project and those in a nearby "control" area. Ideally the control sites should be selected in an area meteorologically similar to the target, but one that would be unaffected by the seeding (or seeding from other adjacent projects). The historical data (e.g., precipitation) in both the target and control areas are taken from past years that have not been subject to cloud seeding activities in either area. These data are evaluated for the same seasonal period as that of the proposed or previous seeding. The target and control sets of data for the unseeded seasons are used to develop an equation (typically a linear regression) that estimates the amount of target area precipitation, based on precipitation observed in the control area. This regression equation is then applied to the seeded period to estimate what the target area precipitation would have been without seeding, based on that observed in the control area(s). This allows a comparison between the predicted target area natural precipitation and that which actually occurred during the seeded period to determine if there are any differences potentially caused by cloud seeding activities.

This target and control technique works well where a good historical correlation can be found between target and control area precipitation. Generally, the closer the target and control areas are in terms of elevation and topography, the higher the correlation will be. Control sites that are too close to the target area, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, a correlation coefficient (r) of 0.90 or better would be considered excellent. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set would be explained by the regression equation used to predict the variable (expected precipitation or snowpack) in the seeded years. An equation indicating perfect correlation would have an r value of 1.0.

Development of Target/Control Evaluation Method for the upper Snake River Basin

North American Weather Consultants (NAWC) had originally proposed that the development of this evaluation method be completed ***a priori***, i.e. prior to the start of the cloud seeding program on December 1, 2007. Due to delays in contracting, this was not possible. This approach would have unequivocally eliminated any question of possible bias on NAWC's part in selection of the control sites. In other words, there would be no way we would know the outcome of the evaluation based upon the control sites that were selected before the cloud seeding began as would be the case had we developed the evaluation equations after the end of the seeding program when the 2007-2008 winter data were available. Since we are completing this analysis in late February, the question of potential bias on our part is still low since there is over a month of seeding yet to be performed. In fact, at this time, we would only have two months of manual snow course observations available to us if we chose to consider this information (which we have not) since these measurements are scheduled to occur on or about the first of each winter month (typically January through April or May). Subsequent sections will indicate the importance of these manual snow course observations in the development of the evaluation methodology.

Figure 1 provides the approximate target area and associated ground generator seeding locations for the 2007-2008 upper Snake River cloud seeding program. A local group, Let it Snow headquartered in Clark County, was selected through a competitive bid process to conduct this program for the 2007-2008 winter season. It is perhaps worth mentioning that NAWC had also bid on the performance of this work.

Following the award of the contract to Let it Snow, North American Weather Consultants was contacted by the High Country Resource Conservation and Development Council and subsequently by the Idaho Water Resource Board (IDWR) concerning the development of an evaluation method that could be used to assess the potential impact of cloud seeding in this area for the 2007-2008 winter season. Both groups elected to fund this evaluation. In the case of the IDWR, a separate task to perform this work was added to another contract that had been awarded to NAWC to conduct a weather modification feasibility study for the upper Snake River Basin in Idaho.

NAWC examined several different types of data for possible use as target and control data for an evaluation of this program. NRCS SNOTEL sites, located in mountainous areas of the state, report both precipitation and snow water content data throughout the year. The SNOTEL sites were typically installed at prior manually observed snow course sites. The establishment of SNOTEL sites began in 1981 at most sites. Precipitation gage data, as well as manual snowcourse data, is available for most of these sites for years prior to 1981. These data were utilized along with the post-1981

SNOTEL data. The manual snowcourse data at these sites was compared to the SNOTEL snow water data for the first 10 years or so after installation of the SNOTEL sites. Adjustments were made by the NRCS to the snowcourse data to match, in as much as possible, the SNOTEL data. Sites that continue to be operated as manual snowcourses provide snow water content measurements near the first of each month during the winter

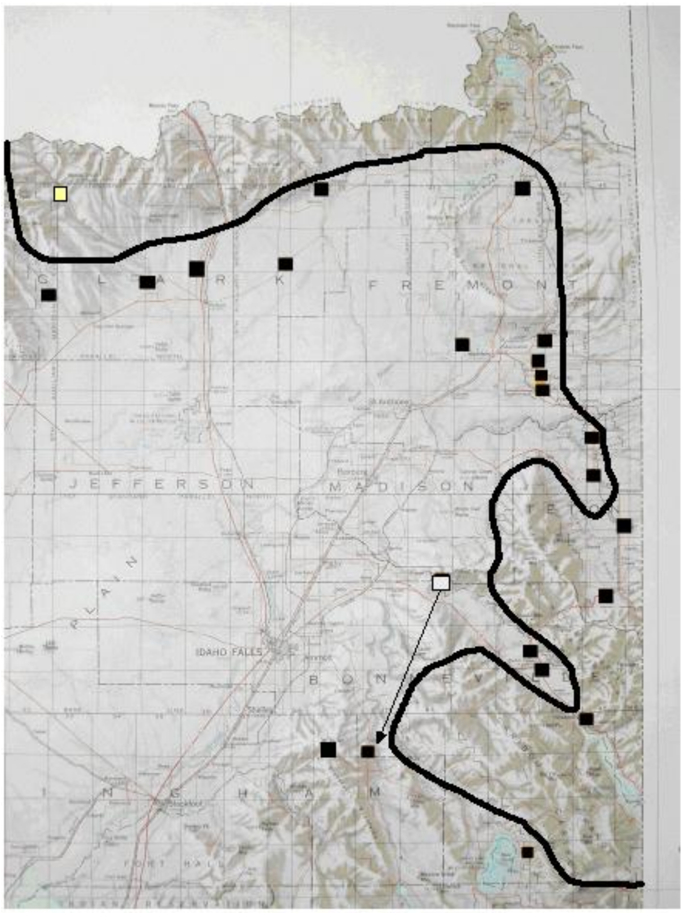

Figure 1. Map showing target area and seeding generator sites for the 2007-2008 upper Snake Operational Seeding Program (one generator site, white box, moved during the season; one new generator site, yellow box, added during the season)

and spring. The measurements are normally made within a few days before or after the first of the month at these snowcourse locations. NWS co-op sites, generally in valley locations, provide monthly precipitation totals throughout the year. Evaluations of both precipitation and snow water content are viable using these different data sources. NAWC personnel entered available data from these sources into data files for additional analysis.

For the precipitation evaluation (December – March period), both SNOTEL precipitation data (as well as pre-1981 gage data) and valley co-op site data were examined. The co-op data was considered only for sites with a good stable record and with minimal missing data. Estimates were made in a few cases for months with 3 or more missing days, using data from nearby sites (it turned out for other reasons that none of the valley co-op sites were included in the final equations anyway). Double-mass plots, an engineering technique where data are accumulated sequentially for two locations and plotted on a graph, were produced for both the SNOTEL and co-op sites and sites. Questionable sites were eliminated based on these plots. Figure 2 provides an example of a plot of December through March precipitation data with a break in the relationship between two stations (Giveout and Pine Creek Pass). This plot indicates questionable data at one of the sites. Comparison of the Giveout site with another site (Sheep Mountan) indicates a stable relationship (Figure 3). It was therefore concluded that the Pine Creek Pass site had some discontinuity in its data, and it was among those excluded from the development of the regression equations.

For the snow water content evaluations (April 1st), both SNOTEL snow water data (including NRCS-adjusted pre-1981 snowcourse data for these sites) and data from current snowcourse sites were considered. Double-mass plots were made in this case also with questionable sites eliminated. Control site combinations best correlated with sites located in the target area were selected.

An historical period beginning in 1961 was selected on which to base the development of the regression equations. NAWC had conducted winter seeding programs in the target area shown in Figure 1 during the 1989, 1993 and 1995 water years (Risch, et al, 1995). It is NAWC's understanding that winter cloud seeding programs were subsequently conducted during the 1997 through 2007 water years. These seeded seasons were excluded from the data set, which resulted in 30 years of data on which the regression equations would be developed. Sites without records going back to 1961 were not considered. In addition, the target area was divided into a "northern" portion (areas north of the Ashton area) and "eastern" portion (south and east of the Ashton area) due to significant climatological and terrain differences between these two areas. These two areas are indicated on Figure 4. Regression equations for precipitation and snow water content were considered for each portion; it was discovered that a precipitation evaluation was not feasible for the eastern portion. This is because there is only one precipitation measurement site (Pine Creek Pass) in this portion of the target and double-mass plots showed poor precipitation data reliability at that SNOTEL site (refer to Figures 2 and 3).

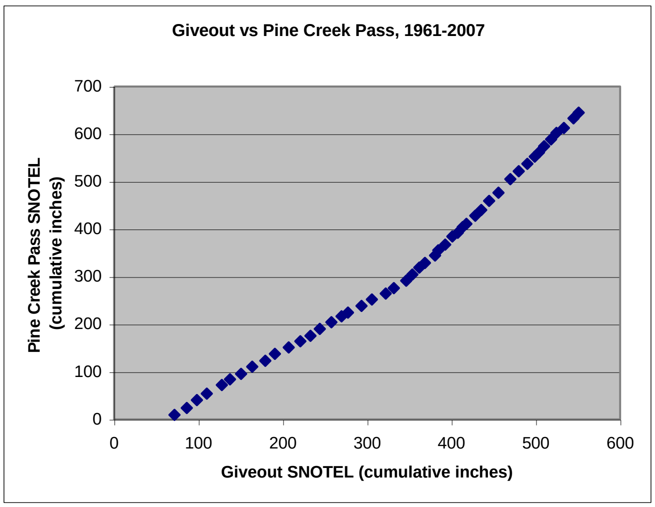

Figure 2 Pine Creek Pass plotted again the Giveout SNOTEL (site shows very poor agreement)

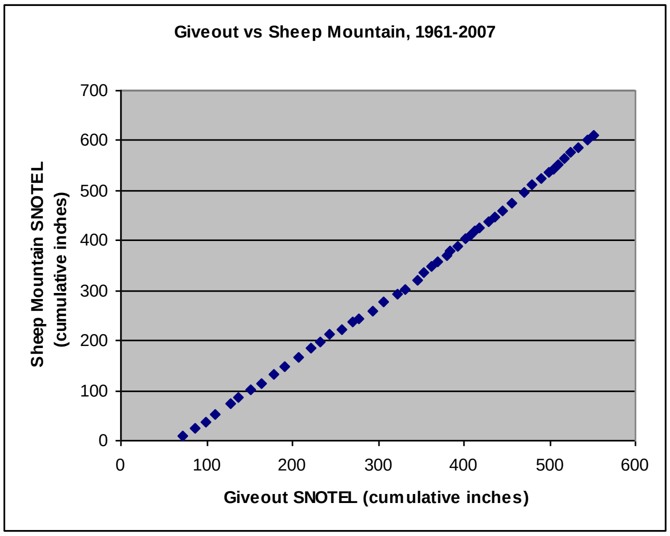

Figure 3 Sheep Mountain plotted again the Giveout SNOTEL (plot shows relatively good agreement)

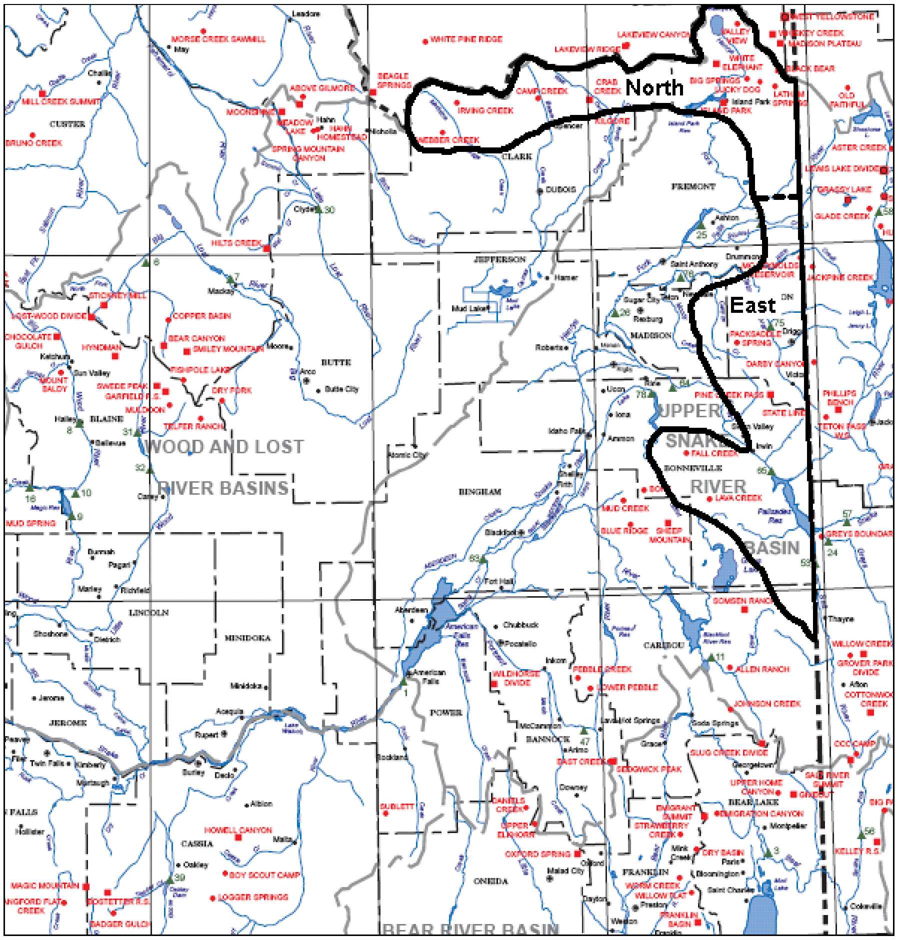

Figure 4 Target area division between "north" and "east", overlain on a map with NRCS SNOTEL and manual snowcourse site locations

Table 1 contains a list of sites excluded from consideration due to the double-mass plot analyses. Table 2 provides target and control sites selected for the evaluations, as well as the resulting linear and multiple linear equations. Figures 5 through 7 provide the locations of the target and control sites for the North target precipitation and snow water content, and the East target snow water content regression equations.

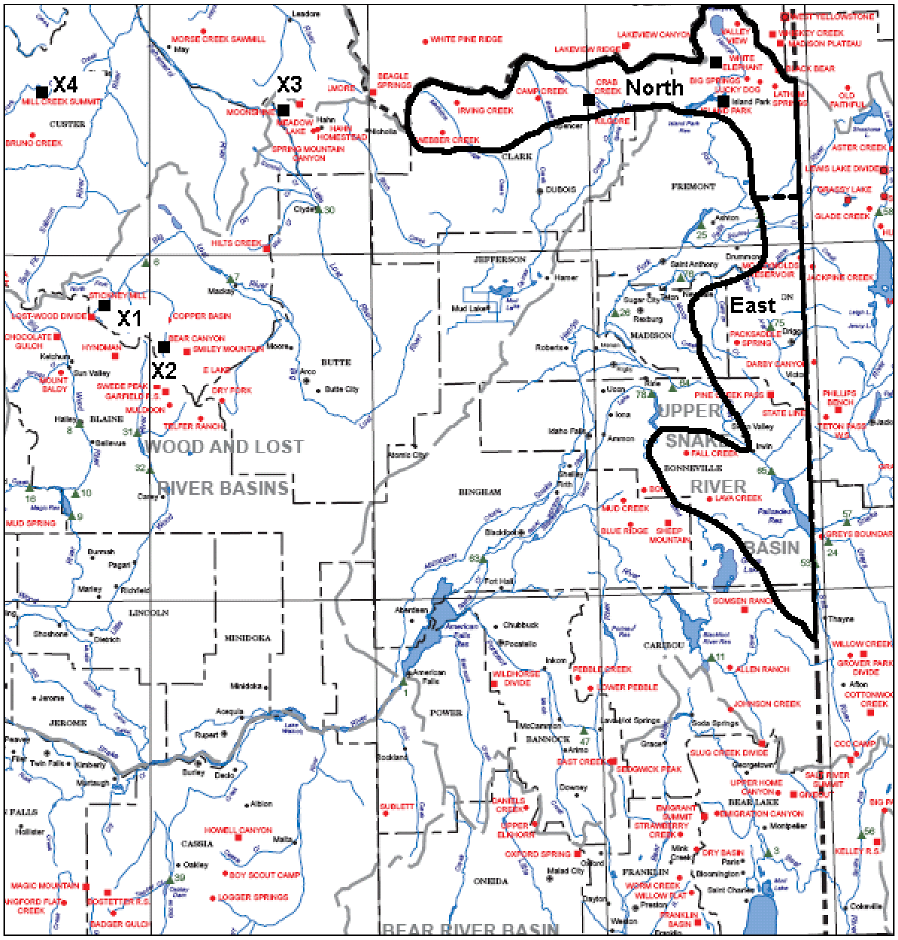

Figure 5 Map with final precipitation evaluation sites for the North target highlighted as black squares (control sites labeled to correspond with Table 2)

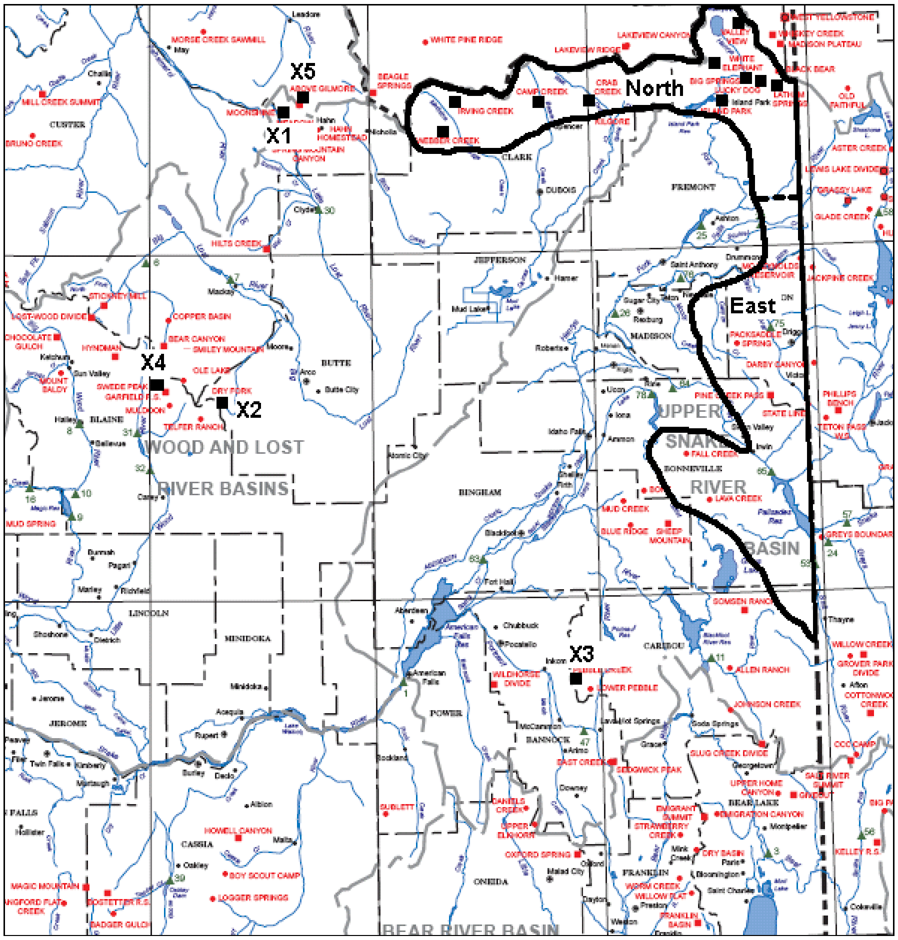

Figure 6 Map with final snowpack evaluation sites for the North target area

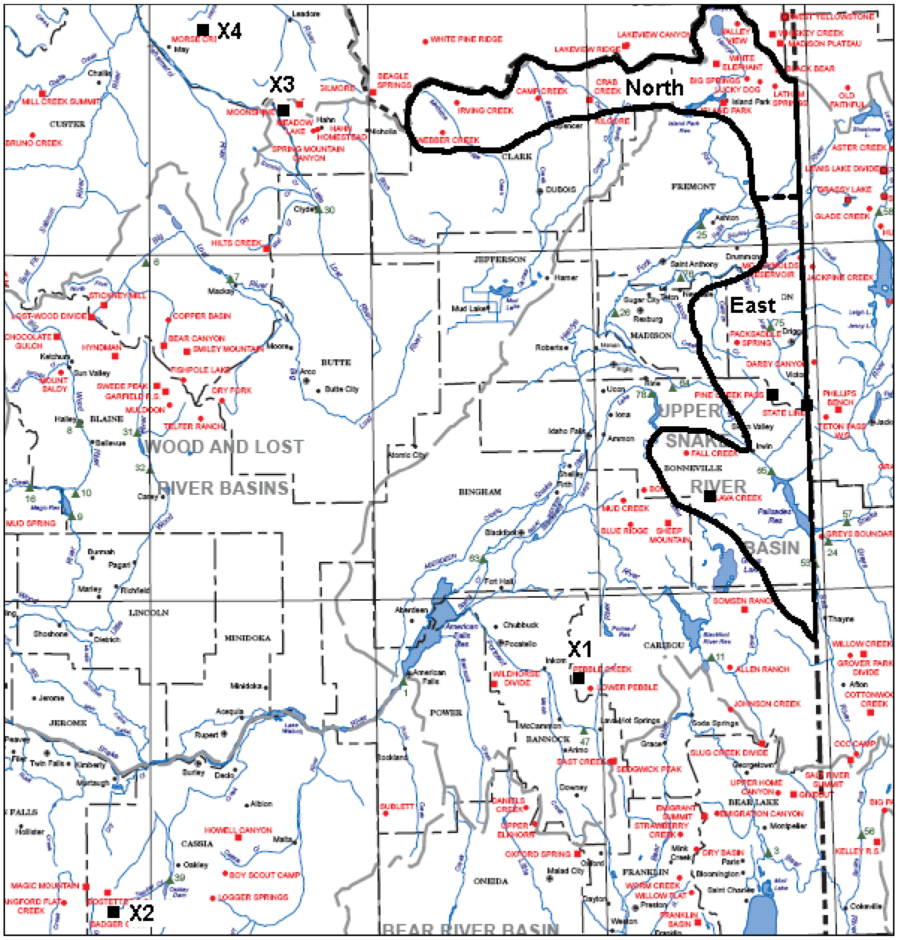

Figure 7 Map with final snowpack evaluation sites for the East target area

Table 1
Sites Excluded Based on Double Mass Plots

Dec-Mar Precip (SNOTEL)
Howell Canyon
Hilts Creek
Pine Creek Pass
Beagle Springs
Dec-Mar Precip (NWS Co-op)
Hamer 4NW
Dubois Exp Station
April 1 Snow (SNOTEL)
Bear Canyon
Oxford Spring
April 1 Snow (Snowcourse)
Langford Flat Creek
Daniels Creek
Bone

The difference between a linear and a multiple-linear equation is that for a linear equation all the potential control sites data for a specific season are averaged together. An equation is then developed between the single control area average values by season versus the single average target area values. Multiple-linear equations are those that allow the regression technique to consider individual site data instead of an average to correlate with the average target area values. In this manner, the regression technique weights the individual correlation of each control site with the target area average to obtain the best correlation.

In this analysis there were only very small differences indicated in the use of linear versus multi-linear equations. This conclusion is based on the very high and similar r values found using either technique. Recall that a perfect correlation would have an r value of 1.0. Therefore, the r values of .95 achieved in this analysis are considered quite high. This means that use of the selected control sites to predict the natural target area precipitation or snow water content for the 2007-2008 winter season should provide a good estimate. These high correlations should strengthen our ability to detect any differences that might be attributed to the seeding program.

This regression equation development work was completed in late February 2008 (Griffith and Yorty, 2008), which is an important point since we cannot be accused of selecting control sites that yielded a desired indication. This could be possible if the equations were developed following the completion of the seeding activities.

Table 2
Regression Equations

North Target – December through March Precipitation:

Control (X)	Target (Y)
Stickney Mill SNOTEL (X_1)	Crab Creek SNOTEL
Bear Canyon SNOTEL (X_2)	White Elephant SNOTEL
Moonshine SNOTEL (X_3)	Island Park SNOTEL
Mill Creek Summit SNOTEL (X_4)	

Linear: $Y = 1.05(X) + 3.9$ $(r = 0.94)$
Multiple Linear: $Y = 0.56(X_1) + 0.21(X_2) + 0.21(X_3) + 0.12(X_4) + 4.5$ $(r = 0.95)$

North Target – April 1st Snowpack:

Control (X)	Target (Y)
Moonshine SNOTEL (X_1)	Crab Creek SNOTEL
Dry Fork snowcourse (X_2)	Island Park SNOTEL
Pebble Creek snowcourse (X_3)	White Elephant SNOTEL
Swede Peak SNOTEL (X_4)	Lucky Dog snowcourse
Above Gilmore snowcourse (X_5)	Big Springs snowcourse
	Valley View snowcourse
	Camp Creek snowcourse
	Irving Creek snowcourse
	Webber Creek snowcourse
	Latham Springs snowcourse

Linear: $Y = 1.05(X) + 3.4$ $(r = 0.95)$
Multiple Linear: $Y = 0.54(X_1) + 0.10(X_2) + 0.19(X_3) + 0.19(X_4) + 0.03(X_5) + 3.6$
$(r = 0.96)$

East Target – April 1 Snowpack:

Control (X)	Target (Y)
Pebble Creek snowcourse (X_1)	Pine Creek Pass SNOTEL
Badger Gulch snowcourse (X_2)	Lava Creek snowcourse
Moonshine SNOTEL (X_3)	State Line snowcourse
Morse Creek Sawmill snowcourse (X_4)	

Linear: $Y = 1.05(X) + 2.4$ $(r = 0.95)$
Multiple Linear: $Y = 0.30(X_1) + 0.28(X_2)+ 0.25(X_3) + 0.15(X_4) + 2.82$
$(r = 0.95)$

Results

The next step in this work was to collect the relevant target and control data from the 2007-2008 winter season once the winter season ended on March 31, 2008. The target and control station information was inserted into the appropriate equation provided in Table 2. In this manner, predictions of the average natural December-March target precipitation (for the north target area) or average target area April 1st snow water content (for both the north and east target areas) were obtained. These predicted amounts were then compared to the observed (actual) precipitation or snow water content values to see if there were any indicated differences that potentially could be attributed to the cloud seeding program. Calculations were also made for the historical seeded winter seasons of 1997-2007. Originally, we were only contracted to provide estimates for the 2007-2008 winter season (WY 2008) but, once the evaluation equations were developed, it was a simple matter to determine and include the 1997-2007 estimates. It should be understood that we did not look at the possible seeding effects from these earlier seeded seasons in determining the mix of target and control sites on which to base our evaluations. NAWC has very little information on these historical seeded years, so some caveats need to be attached to these results:

- The duration of the seeded periods are unknown. We assume that the typical operational period was December through March.
- It is assumed that seeding did occur during all of these winter seasons and that both the northern and eastern areas were targeted.

Tables 3-8 provide the linear and multi-linear equation method calculated values and results for all of the seeded seasons. Summarized results for the snow water equivalent evaluations are shown in Table 9 and for the precipitation data evaluations in Table 10.

Table 3 North Target, April 1st Snow Water Content, Linear Regression Equation Results

Comment [.1]: 2003 values missing?

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1997	18.22	25.02	22.55	1.11	2.47
1998	11.44	15.16	15.43	0.98	-0.27
1999	15.58	20.15	19.77	1.02	0.38
2000	10.96	16.21	14.93	1.09	1.28
2001	5.54	8.78	9.24	0.95	-0.46
2002	9.88	14.90	13.79	1.08	1.11
2003	#VALUE!	11.91	#VALUE!	#VALUE!	#VALUE!
2004	8.18	15.22	12.01	1.27	3.21
2005	10.26	14.75	14.19	1.04	0.56
2006	18.02	19.94	22.34	0.89	-2.40
2007	5.96	9.57	9.68	0.99	-0.11
2008	**13.7**	**18.7**	**17.80**	**1.05**	**0.93**

Mean*	11.6		16.2	15.6	1.04	0.61

* missing data, 2003

Table 4 North Target, April 1st Snow Water Content, Multiple-Linear Regression Equation Results

YEAR	Pebble Creek	Badger Gulch sc	Moonshine	Morse ck Sawmill sc	YOBS	YCALC	RATIO	EXCESS
1997	18.40	18.60	14.80	10.90	24.87	18.80	1.32	6.07
1998	14.30	11.50	8.90	7.10	16.23	13.56	1.20	2.68
1999	15.80	13.80	13.00	8.40	15.63	15.85	0.99	-0.22
2000	11.90	11.90	8.30	8.30	14.50	13.00	1.12	1.50
2001	6.40	6.10	3.70	4.90	9.27	8.09	1.15	1.18
2002	12.40	15.80	5.90	8.20	12.47	13.64	0.91	-1.17
2003	7.50	4.20	4.70	9.00	12.87	8.76	1.47	4.11
2004	10.90	13.00	7.00	5.60	12.47	12.28	1.02	0.19
2005	12.50	9.80	6.90	5.40	11.67	11.79	0.99	-0.13
2006	19.90	18.20	14.30	11.00	18.50	19.02	0.97	-0.52
2007	6.80	5.20	5.80	6.20	10.00	8.67	1.15	1.33
2008	**17.6**	**16.8**	**12.6**	**9.1**	**17.53**	**17.24**	**1.02**	**0.29**
Mean	12.9	12.1	8.8	7.8	14.7	13.4	1.10	1.28

Table 5 North Target, December – March Precipitation, Linear Regression Equation Results

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1997	17.13	25.13	21.89	1.15	3.24
1998	8.75	15.10	13.10	1.15	2.00
1999	12.40	18.67	16.93	1.10	1.73
2000	10.65	15.67	15.10	1.04	0.57
2001	4.70	7.57	8.85	0.85	-1.29
2002	9.50	13.80	13.89	0.99	-0.09
2003	10.43	11.53	14.86	0.78	-3.33
2004	10.53	16.33	14.97	1.09	1.37
2005	7.50	14.30	11.79	1.21	2.51
2006	14.78	20.07	19.42	1.03	0.64
2007	7.68	10.97	11.98	0.92	-1.01
2008	**12.0**	**17.9**	**16.46**	**1.09**	**1.44**
Mean	10.5	15.6	14.9	1.04	0.65

Table 6 North Target, December – March Precipitation,
Multiple-Linear Regression Equation Results

YEAR	Stickney Mill	Bear Canyon	Moonshine	Mill Creek Summit	YOBS	YCALC	RATIO	EXCESS
1997	12.80	19.20	13.20	23.30	25.13	21.29	1.18	3.84
1998	6.10	11.20	7.80	9.90	15.10	13.10	1.15	2.00
1999	8.00	14.60	10.50	16.50	18.67	16.24	1.15	2.43
2000	7.20	12.10	10.60	12.70	15.67	14.83	1.06	0.84
2001	3.30	5.10	4.90	5.50	7.57	9.11	0.83	-1.54
2002	6.30	11.40	7.60	12.70	13.80	13.55	1.02	0.25
2003	6.80	12.50	7.50	14.90	11.53	14.31	0.81	-2.78
2004	7.60	13.20	9.90	11.40	16.33	14.98	1.09	1.35
2005	5.70	9.80	6.20	8.30	14.30	12.06	1.19	2.24
2006	11.40	19.10	12.60	16.00	20.07	19.47	1.03	0.59
2007	4.60	7.40	6.80	11.90	10.97	11.49	0.95	-0.53
2008	**8.0**	**13.4**	**11.8**	**14.6**	**17.9**	**16.03**	**1.12**	**1.87**
Mean	7.3	12.4	9.1	13.1	15.6	14.7	1.06	0.88

Table 7 East Target, April 1st Snow Water Content,
Linear Regression Equation Results

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1997	15.68	24.87	18.81	1.32	6.05
1998	10.45	16.23	13.35	1.22	2.88
1999	12.75	15.63	15.75	0.99	-0.12
2000	10.10	14.50	12.98	1.12	1.52
2001	5.28	9.27	7.94	1.17	1.33
2002	10.58	12.47	13.48	0.92	-1.01
2003	6.35	12.87	9.06	1.42	3.81
2004	9.13	12.47	11.96	1.04	0.50
2005	8.65	11.67	11.47	1.02	0.20
2006	15.85	18.50	19.00	0.97	-0.50
2007	6.00	10.00	8.70	1.15	1.30
2008	**14.0**	**17.5**	**17.09**	**1.03**	**0.44**
Mean	10.4	14.7	13.3	1.10	1.37

Table 8 East Target, April 1st Snow Water Content, Multiple-Linear Regression Equation Results

YEAR	Pebble Creek	Badger Gulch	Moonshine	Morse Cr. Sawmill	YOBS	YCALC	RATIO	EXCESS
1997	18.40	18.60	14.80	10.90	24.87	18.80	1.32	6.07
1998	14.30	11.50	8.90	7.10	16.23	13.56	1.20	2.68
1999	15.80	13.80	13.00	8.40	15.63	15.85	0.99	-0.22
2000	11.90	11.90	8.30	8.30	14.50	13.00	1.12	1.50
2001	6.40	6.10	3.70	4.90	9.27	8.09	1.15	1.18
2002	12.40	15.80	5.90	8.20	12.47	13.64	0.91	-1.17
2003	7.50	4.20	4.70	9.00	12.87	8.76	1.47	4.11
2004	10.90	13.00	7.00	5.60	12.47	12.28	1.02	0.19
2005	12.50	9.80	6.90	5.40	11.67	11.79	0.99	-0.13
2006	19.90	18.20	14.30	11.00	18.50	19.02	0.97	-0.52
2007	6.80	5.20	5.80	6.20	10.00	8.67	1.15	1.33
2008	**17.6**	**16.8**	**12.6**	**9.1**	**17.53**	**17.24**	**1.02**	**0.29**
Mean	12.9	12.1	8.8	7.8	14.7	13.4	1.10	1.28

Tables 9 and 10 summarize the results obtained using the historical target/control methodology for April 1st snow water content, aka snow water equivalent (SWE), and December through March precipitation. A reminder, there were/are not enough high elevation precipitation stations in the East target to establish December through March precipitation regression equations. Results are shown for both the linear and multiple-linear regression equations.

Table 9 Results for April 1st Snow Water Content

Target	Predicted Apr. 1 SWE	Observed Apr. 1 SWE	Ratio Predicted/Observed SWE	Observed minus Predicted SWE (inches)
North Linear Eq. WY 2008	17.8	18.7	1.05*	0.93
North Linear Eq. WY 1997-2008	15.6	16.2	1.04*	0.61
North Multi-Linear Eq. WY 2008	17.2	17.5	1.02	0.29

North Multi-Linear Eq. WY 1997-2008	13.4	14.7	1.10	1.28
East Linear Eq. WY 2008	17.1	17.5	1.03	0.44
East Linear Eq. WY 1997-2008	13.3	14.7	1.10	1.37
East Multi-Linear Eq. WY 2008	17.2	17.5	1.02	0.29
East Multi-Linear Eq. WY 1997-2008	13.4	14.7	1.10	1.28

* Missing data in WY 2003, not included in calculations.

Table 10 Results for December – March Precipitation, North Area

Target	Predicted Dec. – Mar. Precipitation (inches)	Observed Dec. – Mar. Precipitation (inches)	Ratio Predicted/Observed Dec. – Mar. Precipitation	Observed minus Predicted Dec. – Mar. Precipitation (inches)
North Linear Eq. WY 2008	16.5	17.9	1.09	1.44
North Linear Eq. WY 1997-2008	14.9	15.6	1.04	0.65
North Multi-Linear Eq. WY 2008	16.0	17.9	1.12	1.87
North Multi-Linear Eq. WY 1997-2008	14.7	15.6	1.06	0.88

Discussion

It is noted that the estimates from the linear and the multi-linear equations provide very similar estimates. This is a desirable result that indicates stability in the target and control relationships. Discussion of the results is broken down into the North and East target areas.

North Target Area

The ratios of observed over calculated April 1st snow water content for WY 2008 using the linear and multi-linear equations suggest a 2-5 % increase in water content. Results for all of the seeded seasons, WY 97-08, suggest average increases in water content of 4-10%. The average estimated increases in April 1st snow water content for WY 08 are in the range of 0.29 to 0.93 inches of additional water content. Similar estimates for the entire seeded period (WY 97-08) range from 0.61 to 1.28 inches.

The ratios of observed over calculated December through March precipitation using the linear and multi-linear equations suggest a 9-12 % increase in water content for WY 2008. Results for all of the seeded seasons, WY 97-08, suggest average increases in December through March precipitation of 4-6%. The average estimated increases in December through March precipitation for WY 08 are in the range of 1.44 to 1.87 inches of additional water content. Similar estimates for the entire seeded period (WY 97-08) range from 0.65 to 0.88 inches.

East Target Area

The ratios of observed over calculated April 1st snow water content for WY 2008 using the linear and multi-linear equations suggest a 2-3 % increase in water content. Results for all of the seeded seasons, WY 97-08, suggest average increases in water content of 10%. The average estimated increases in April 1st snow water content for WY 08 are in the range of 0.29 to 0.44 inches of additional water content. Similar estimates for the entire seeded period (WY 97-08) range from 1.28 to 1.37 inches.

Other Considerations

The estimated increases in snow water content or December through March precipitation are area averages and can be visualized as being spread over the target area. For example, the 0.29 to 0.93 inches of additional snow water content for the northern target area in WY 2008 could be assumed to be distributed equally over the target area. The results for the northern area April 1st snow water contents may be more representative of possible seeding effects since there were more target area gages available for inclusion in that analysis. Some of the results for WY 1997 provide high estimated increases in snow water content and December through March precipitation. These increases may be overstated perhaps due to some persistent weather pattern that favored the target areas in terms of precipitation during that period. This points out an observation we have made over the years when employing individual season analysis.

One season's result may not be indicative of the long-term effects of cloud seeding. Averages for multi-season programs provide much better indications of the average increases (or decreases) in target area precipitation that may be attributed to cloud seeding activities.

References

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