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ECONOMIC FEASIBILITY ASSESSMENT OF WINTER CLOUD SEEDING IN THE BOISE RIVER DRAINAGE, IDAHO

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

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

1. INTRODUCTION

North American Weather Consultants (NAWC) conducted winter cloud seeding programs over the Boise River Drainage above Lucky Peak Dam from 1993-1996. These programs were conducted for the Boise Project Board of Control. Wet winter seasons beginning in the 1996 water year resulted in curtailment of the program. The goal of the programs was to augment higher elevation snowfall which would result in augmented streamflow. This augmented streamflow would be used to generate additional electrical power from a power plant installed on Lucky Peak Dam and provide additional water supplies for downstream irrigation. The application of cloud seeding to target areas in an attempt to produce additional hydroelectric generation is a rather common application of cloud seeding(Griffith, 1993). A network of 20 ground based silver iodide generators was used to seed portions of winter storms that impacted the target area. The operational period varied somewhat from water year to water year within the November 1st to May 31st period. Figure 1 provides the location of the target area and the three reservoirs (Lucky Peak, Arrowrock and Anderson Ranch).

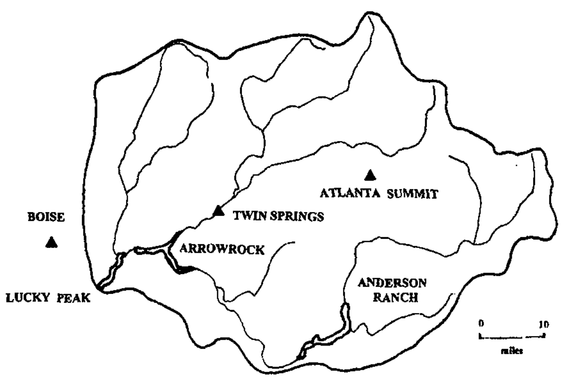

Figure 1. Location of target area with key locations shown.

A question posed by the sponsor of the program asked whether the additional streamflow resulting from the cloud seeding program would generate additional hydroelectric power since water released in the spring and early summer months might exceed the capacity of the power plant turbines. Data were obtained by NAWC to directly address this question. In the process of analyzing data to answer this question, additional sources of information were examined. The results of these analyses were compiled, forming a basic economic assessment of the feasibility of conducting winter cloud seeding programs in the Boise River Drainage. The following sections summarize this assessment.

2. ANALYSES

2.1 Frequency of Occurrence of Releases from Lucky Peak that Exceed the Turbine Capacities

Mr. James Doty of the Bureau of Reclamation (BUREC) offices in Boise provided NAWC with daily data files of the calculated total water release from Lucky Peak Dam(QD) and releases through its power plant (QV). Both measurements were reported as average daily flow rates in cfs. The QD records dated back to 1955 but the QV records only dated back to 1990.

The data from these two sets of hydrologic data were compared in the following manner. Days on which the QD value exceeded the QV value by 200 cfs were flagged. This 200 cfs value was selected since there was some difference noted in the two values (for example some daily values of water passing through the turbines were greater than the reported total release for the day) to minimize possible errors in the two calculated values. A summary graph of daily QD and QV values covering 10 complete years and a portion of the 2001 water year is provided in Figure 2. Figure 3 provides a plot of the difference in the two values when QD exceeded QV by at least 200 cfs on a daily basis. Days that met these criteria were ones that were considered to have some water lost to hydroelectric power production. Figure 3 shows the dates or periods when the water released from the dam exceeded that which passed through the turbines. The results are rather interesting. In some years there was little difference (i.e., WY 91,92,94,99) and other water years when there were substantial differences (i.e., WY 93,95,96,97,98,00). As expected, the largest differences occurred during the months of April, May and June; the peak snow melt runoff months. Two tables were prepared summarizing some of the relevant information. Table 1 provides monthly totals for QD and QV by water year. Table 2 summarizes the daily differences between QD and QV (when daily values of QD - QV > 200cfs) on a monthly basis by water year.

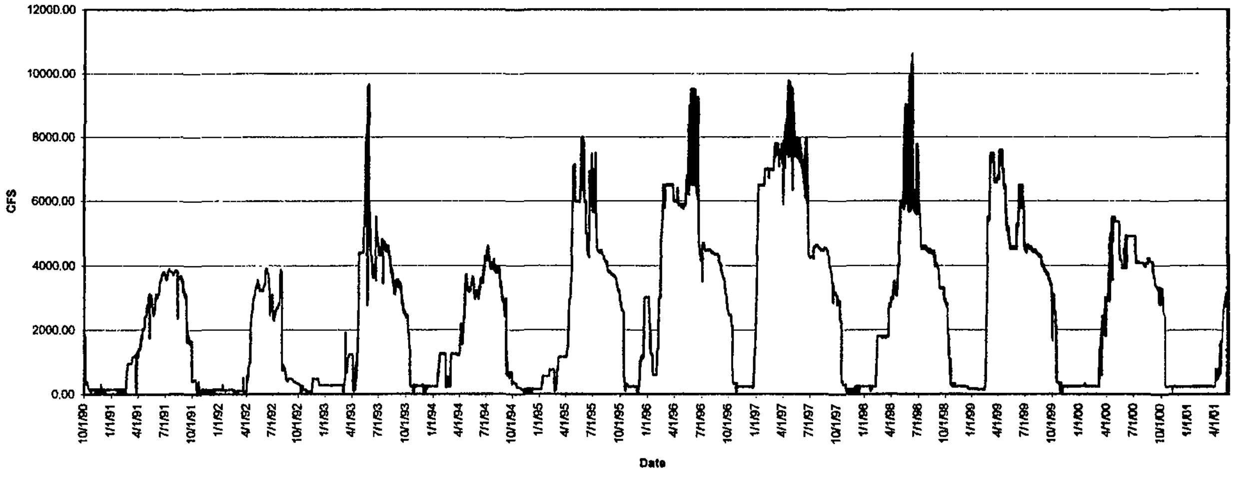

Figure 2. Plot of daily QD and QV from October 1, 1990 through April 1, 2001 (values in cfs). Periods that QD exceeded QV are shaded in black.

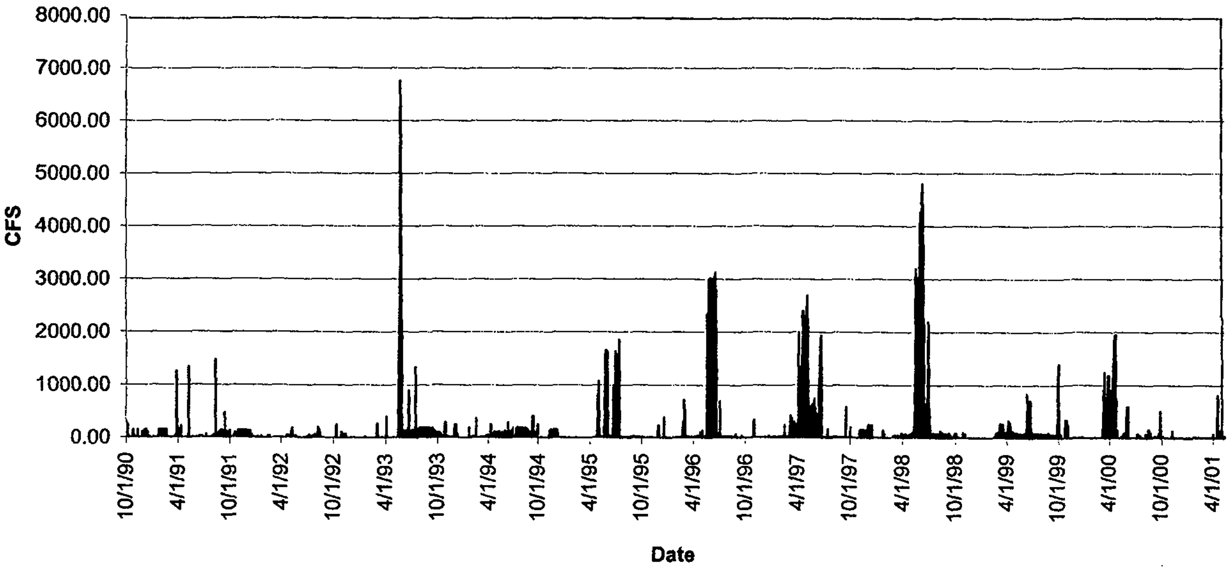

Figure 3. Plot of days when QD exceeded QV by 200 cfs, for the period October 1, 1990 through April 1, 2001.

Table 1. Lucky Peak Summation of Daily Flows, Total Flow (QD) and flow through the turbines (QV) in cfs

		WR										
Month	Data	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
OCT	Sum of QD	14,363	9,049	6,173	34,148	8,531	36,508	39,375	42,900	41,656	44,393	46,832
	Sum of QV	13,567	8,104	5,133	31,684	8,485	36,196	38,031	42,383	40,995	39,223	46,722
NOV	Sum of QD	4,953	4,163	7,926	7,724	4,648	7,114	7,283	4,635	7,239	7,234	7,297
	Sum of QV	2,501	21	6,747	7,094	1,269	6,018	6,971	398	7,143	6,100	6,858
DEC	Sum of QD	4,621	4,172	9,993	7,566	4,758	54,456	18,295	7,599	6,518	7,573	7,590
	Sum of QV	2,814	2,231	9,946	5,790	3,493	53,669	17,929	3,931	6,468	7,376	7,378
JAN	Sum of QD	4,572	4,179	8,286	19,355	13,137	42,925	186,240	7,566	5,042	7,689	7,616
	Sum of QV	3,107	3,994	8,262	18,959	13,129	42,737	185,525	6,750	4,973	7,631	7,197
FEB	Sum of QD	9,657	3,612	7,563	20,924	15,882	122,800	196,260	34,511	50,906	7,076	6,865
	Sum of QV	7,008	3,516	7,460	20,219	15,879	119,122	195,227	34,352	49,912	6,917	6,624
MAR	Sum of QD	34,802	3,504	28,515	38,145	33,074	200,220	234,500	64,415	214,054	59,094	7,571
	Sum of QV	31,270	3,450	27,521	37,593	33,016	199,314	228,306	63,242	208,687	44,182	7,261
APR	Sum of QD	57,054	56,668	54,621	76,570	103,023	179,530	268,210	105,780	206,257	139,187	38,142
	Sum of QV	56,420	56,244	54,058	74,137	99,333	178,354	220,283	103,863	201,111	112,461	34,717
MAY	Sum of QD	88,289	102,937	200,313	103,460	208,300	240,920	254,570	241,180	146,953	142,053	38,717
	Sum of QV	86,951	101,520	155,878	100,257	190,345	198,966	226,861	181,061	144,251	140,660	38,254
JUN	Sum of QD	104,121	99,012	133,520	108,750	176,090	221,930	204,890	235,420	177,562	145,018	
	Sum of QV	103,837	98,959	128,268	104,857	163,151	170,877	184,627	171,203	164,773	141,655	
JUL	Sum of QD	116,828	86,630	143,370	130,770	170,950	139,970	138,480	151,680	141,803	132,340	
	Sum of QV	116,708	85,459	137,308	126,386	154,929	138,172	137,665	147,819	139,314	131,606	
AUG	Sum of QD	114,420	32,823	118,350	112,550	125,890	135,500	139,860	137,000	134,084	127,725	
	Sum of QV	110,873	31,157	112,583	107,323	125,140	134,512	139,250	134,246	131,647	126,229	
SEP	Sum of QD	66,859	12,390	91,680	39,617	104,820	100,926	105,501	104,390	109,613	103,993	
	Sum of QV	63,038	12,390	87,380	36,345	104,150	100,480	104,493	102,814	105,361	102,554	
Total Sum of QD		620,540	419,138	810,312	699,579	969,104	1,482,799	1,793,464	1,137,076	1,241,687	923,376	160,629
Total Sum of QV		598,095	407,044	740,542	670,644	912,319	1,378,416	1,685,170	992,060	1,204,634	866,595	155,010

Annual totals are also provided. The annual differences (based on daily flow rate measurements) from Table 2 vary from zero to approximately 128,000 cfs (WY 98). The average over 10 years is 50,661 cfs (approximately 100, 309 acre feet) per water year.

Table 2. Summation of Daily Flows by Month where the Total Flow exceeded flow through the turbines by 200 cfs

Sum of Difference	WR											
Month	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Total
OCT	253		491	813			1,095	209		4,670		7,531
NOV						713				698		1,411
DEC				1,483		391		3,421				5,295
JAN				202								202
FEB				364		3,358	249					3,972
MAR	2,720		535				5,197		3,158	14,486		26,095
APR	223		400	257	3,281		47,927		2,830	25,315	2,050	82,281
MAY	1,337		44,327		17,327	41,264	27,709	59,110		426		191,500
JUN			1,731	297	12,310	50,672	19,921	63,837	11,587	3,363		163,719
JUL			1,338		15,538	691		1,548				19,116
AUG	1,471											1,471
SEP	472			1,787			587		2,411	816		6,073
Total	6,476		48,822	5,203	48,456	97,090	102,684	128,125	19,986	49,774	2,050	508,666
Total Acre Feet	12,832		96,668	10,302	95,943	192,238	203,314	253,688	39,572	98,553	4,059	1,007,159

2.2 Winter Cloud Seeding Program, 1993 - 1996

NAWC operated a winter cloud seeding program during the water years of 1993-1996, designed to affect the Boise River basin above Lucky Peak Dam. The program was operational during the following periods: Dec. 10, 1992 - May 31, 1993; Nov. 22, 1993 - Apr. 30, 1994; Nov. 15, 1994 - Apr. 15, 1995 and Nov. 1, 1995 - Mar. 31, 1996. The design, operation and evaluation of this program were similar to ones previously conducted by NAWC in Utah (i.e., Griffith, et al, 1991). The intended target area along with ground generator locations used in the 1995-96 program are shown in Figure 4. The same generator locations were used in each of the four seeded seasons. Elevations of the generators ranged from 1000 to 5400 feet msl. Each generator emitted eight grams of silver iodide per hour of operation. The generators were operated by local residents when they were called by one of NAWC's meteorologists. Decisions on when the generators were operated were based on generalized seeding criteria provided in Table 3.

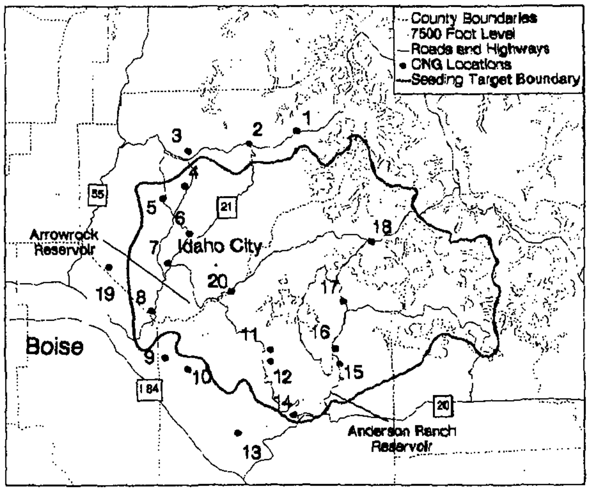

Figure 4. Target area and ground based generator locations, 1993-1996

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Table 3. NAWC Winter Cloud Seeding Criteria

1) Cloud Bases are below the mountain barrier crest.
2) Low-level wind directions and speeds that would favor the movement of the silver iodide particles from their release points into the intended target area.
3) No low level atmospheric inversions or stable layers that would restrict the vertical movement of the silver iodide particles from the surface to at least -5°C (23°F) level or colder.
4) Temperature at mountain barrier crest height expected to be -5°C (23°F) or colder.
5) Temperature at the 700 MB level (approximately 10,000 feet) expected to be warmer than -15°C (5°F).

These programs were evaluated using average April 1st snow pack water content data. These data were obtained from Soil Conservation Service snow course and Natural Resource Conservation Service Snotel sites. NAWC normally conducts an evaluation of the apparent effects of seeding in the preparation of an annual operations report for each of its operational programs. For this program, ten target area and seven control area sites were identified with long term historical records. Control stations were selected in close proximity to the target stations and at similar elevations in order to obtain as strong correlations as possible. These stations were used to conduct an evaluation of the program. Once these stations were selected at the end of the first of the four-year seeding program, they remained unchanged throughout the four-year period. The locations of these sites are provided in Figure 5. Information on these sites is provided in Tables 4 and 5.

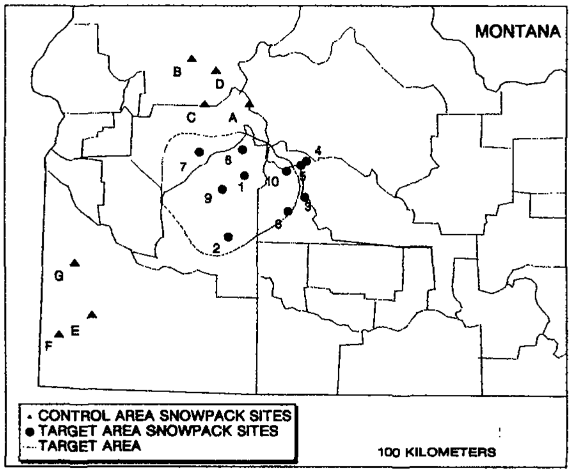

Figure 5. Location of target (1-10) and control (A-G) snotel sites.

Table 4. Target Area Sites - Snowpack

Site ID	Site Name	Site No.	Elev. (Ft)	Lat (N)	Long (W)
1	Atlanta Summit	I15F04	7580	43° 45'	115° 14'
2	Camas Creek Div.	I15F09	5710	43° 16'	115° 21'
3	Dollarhide Summit	I14F08	8420	43° 36'	114° 40'
4	Galena	I14F01	7440	43° 53'	114° 40'
5	Galena Summit	I14F12	8780	43° 51'	114° 43'
6	Graham G.S.	I15F14	5690	43° 57'	115° 16'
7	Moores Creek Summit	I15F01	6100	43° 55'	115° 40'
8	Soldier R.S.	I14F11	5740	43° 29'	114° 49'
9	Trinity Mountain	I15F05	7770	43° 38'	115° 26'
10	Vienna Mine	I14F04	8960	43° 48'	114° 51'

Table 5. Control Area Sites - Snowpack

Site ID	Site Name	Site No.	Elev. (Ft)	Lat. (N)	Long (W)
A	Banner Summit	I15E11	7040	44° 18'	115° 14'
B	Big Creek Sum	I15E02	6580	44° 38'	115° 48'
C	Cozy Cove	I15E08	5380	44° 17'	115° 39'
D	Deadwood Summit	I15E04	6860	44° 33'	115° 34'
E	Mud Flat	I16G07	5730	42° 36'	116° 33'
F	Red Canyon	I16G11	6650	42° 26'	116° 50'
G	Silver City	I16F03	6400	43° 00'	116° 44'

The historical base period of 1961-1992 was used to develop a linear regression equation relating the average April 1st snow water contents in the control areas versus the target area. There were no cloud seeding programs conducted in these areas during this period. This equation was $y = -1.68 + 1.16(x)$ where y is the average target area snow water content and x is the average control snow water content. A very strong correlation was provided by this regression equation with an r value of 0.98 (the resulting r^2 value indicates that 96% of the variance is explained by the regression equation). This equation was used to calculate the natural target area snow water content during the four seeded seasons and the results were then compared to the observed average target area snow water content. The target and control sites used in the evaluation were the same for each of the four seasons. All four seeded seasons indicated differences (all increases) in observed water content versus predicted water content. These differences were expressed as percentage increases for each water year (WY) which were: WY 93, 16.5%; WY 94, 6.5%; WY 95, 17.4% and WY 96, 5.0%. The average increase was 12%. This was equivalent to an average increase in snow water content of 2.50". The estimated increases may be somewhat conservative since the seeding continued after April 1st in three of the four seeded seasons. More detail on this evaluation is contained in Risch, et al, 1996. A check on the information provided from the regression equation was conducted for the not seeded winter seasons following termination of seeding (WY 98, 99, 00 and 01). WR 97 was not included in this check due to contamination concerns since cloud seeding was being conducted in an adjacent drainage basin to the north of the Boise drainage (Payette drainage). The expectation would be that the observed over predicted amounts from the regression equation would be near 1.0. This was the case. The average ratio from these four not seeded seasons was 1.02.

2.3 Estimated Increases in Streamflow at Twin Springs

Unimpaired annual average runoff records (cfs) were obtained for the Boise River near Twin Springs (below the confluence of the North and Middle forks) from the USGS for the period 1971-1990. This is a period before any cloud seeding programs were conducted in the area. April 1st snow pack water content values for Atlanta Summit, a centrally located high elevation site within the intended target area of the program, were obtained for this same period from the NRCS. The locations of these sites are provided in Figure 1. These two data sets were compared by developing a linear regression equation between the two sets of data. This equation was $y = 33.2x + 167.5$ where y is annual average runoff at Twin Springs (in cfs) and x is the Atlanta Summit April 1st snow water content (in inches). The two data sets were well correlated $r = .94$ which means 88% of the variance between the two data sets is explained by the regression equation).

The average annual runoff at Twin Springs for the 20-year base period was calculated to be 1252 cfs. When this average runoff value was placed in the above equation, the Atlanta Summit snow water content was 32.7". This average snow water content value was then increased by 12% (the estimated average increase described earlier). When this value (36.6") was inserted into the equation, the resultant average base period streamflow was 1369 cfs. When this value is compared to the 20-year average value (1252 cfs) the difference is a 9.4% increase. This indicates that a 12% increase in Atlanta Summit April 1st snow water content would result in a 9.4% increase in the Twin Springs average annual runoff.

The average annual runoff at Twin Springs for the four seeded years was 1321 cfs (956,404 acre feet). When this amount was multiplied by the calculated increase in runoff (9.4%), the result was 89,902 acre feet on an annual basis. In other words, the estimated increase in the average annual streamflow of the Boise River at Twin Springs was 89,902 acre feet during the four years of the cloud seeding program. If the cloud seeding programs had not been conducted during this four-year period, this analysis suggests the average annual runoff would have been 866,502 acre feet.

2.4 Estimated Increases in Streamflow from the Entire Target Area

Recall that the target area of the cloud seeding program was all of the Boise River Drainage above Lucky Peak Dam. There are no unimpaired runoff records for the inflow to the Anderson Ranch Reservoir which is located upstream of Lucky Peak Dam. NAWC estimated the Anderson Ranch streamflow and the runoff generated by tributaries below the Twin Springs measurement site as follows. An average annual discharge from Lucky Peak Dam was calculated from data in Table 1 for the 10-year period of 1991-2000. This average value was 1,999,220 acre feet. The average annual flow at Twin Springs for this 10-year period was 902,599 acre feet. The difference between these two values is 1,096,621 acre feet. This latter value provides an estimate of the average annual runoff from the Anderson Ranch drainage (South Fork) plus inflow to Lucky Peak from tributaries below Twin Springs. This information was used to calculate the average amount of annual runoff that was generated by the cloud seeding program for the total target area. The 9.4% increase times 1,096,621 acre feet equals an average increase of 103,082 acre feet. Adding the estimated increase from the drainage above Twin Springs to this value, we arrive at a total estimated increase in average annual runoff for the entire target area of 192,984 acre feet during the four year seeded period. The average budget for the conduct of these programs was approximately $85,000 per season. Dividing this cost by the 192,984 acre foot value results in an estimated cost to produce this additional runoff of $0.44 per acre foot. This result is similar to that obtained in an earlier analysis of a long term program conducted by NAWC in Utah that indicated the estimated cost of additional water from this program was costing approximately $1.00 per acre foot (Stauffer, 2001). Even if all the additional runoff cannot all be used in the production of power, it may be used for irrigation.

3. ECONOMIC ASSESSMENT

3.1 Estimated Value of Augmented Streamflow

Comparing the information in Table 2 with the estimated average increase in total streamflow from the cloud seeding program(192,984 af) it is likely that a cloud seeding program in 8 of the 10 water years would produce additional runoff that could essentially all be used in power production. The two years of 1997 and 1998 would probably not have been productive since the amounts of water that bypassed the turbines (203,312 and 253,685 acre feet for these two years) were near or above the potential excess that could result from a cloud seeding program. Additional snowfall produced from the cloud seeding program would, however, be distributed throughout the various elevations of the target area. Augmented runoff would therefore be distributed throughout the snow melt period and beyond (due to the flow from underground recharge). As a consequence, only a small percentage of the augmented runoff would be lost during the spring/early summer peak runoff periods. For illustration, let us assume cloud seeding was conducted in the eight years of WY 91-96 and 99-00. Ignore the fact that cloud seeding was conducted during four of these years. The average loss of runoff to power production in these eight years was 68,261 acre feet. Let us assume half of the additional water that may have resulted from cloud seeding (192,984/2 = 96,492 acre feet) could not be used for power production, although some of this water would still be available for downstream irrigation, leaving 96,492 acre feet available for power production. Discussions with Mr. Tom Nelson (personal communication, August, 2001), the Lucky Peak Dam power plant operator, indicated the average annual power production from Lucky Peak is 320,000 megawatt hours(mwh). The average annual water flow through the Lucky Peak turbines for the 10-year period is 1,872,192 acre feet. Dividing the 320,000 by 1,872,192 results in the average of 0.17 mwh produced per acre foot of water that passes through the turbines. Mr. Nelson indicated the value of this production for the 2001 water year was quite variable ranging from $50-200/mwh. Mr. Nelson expressed the opinion that this value will average $50-60/mwh in the future. Multiplying 96,492 acre feet times 0.17mwh/af would result in 16,409 mwh of additional electricity. Applying a $50/mwh rate results in a conservative estimated average value of the enhanced runoff from cloud seeding for these eight years strictly for power generation of $820,182 per water year.

3.2 Benefit/Cost Estimate

Finally, we can estimate an average benefit/cost ratio strictly from power production by dividing $820,182 by the budgeted cost to conduct the program which is $85,000. The result is an estimated benefit/cost ratio of 9.7/1. This is a very favorable result which suggests that for each dollar spent on cloud seeding approximately $10 dollars of benefit may be realized from augmented Lucky Peak power production. This estimated benefit/cost ratio is significant but not uncommon in the analysis of other programs conducted for hydro-electric power production. For example, an analysis of a summer program conducted in Honduras yielded an estimated 23.5/1 benefit/cost ratio (Griffith and Solak, 1999). Incidentally, this analysis ignores any benefits that would result from increased power production from the BUREC's Anderson Ranch facility. The addition of the value of this water for irrigation purposes would further increase this ratio.

4. SUMMARY AND CONCLUSIONS

NAWC conducted winter cloud seeding programs for the Boise Project Board of Control for the water years of 1993-1996. The target area for these programs was the Boise River Drainage above Lucky Peak Dam. The budgeted annual cost to conduct these programs was approximately $85,000. An evaluation of the effectiveness of these programs indicated an average of a 12% increase in the target area April 1st snow pack water content. There is the potential for a dual benefit from the enhanced streamflow that would result from the program; increases in hydroelectric power production from Lucky Peak Dam (an installed generating capacity of 100mw) and additional water for irrigation.

A question was raised whether the additional runoff potentially produced from the cloud seeding program might be lost to hydroelectric generation since there may be frequent releases from the dam that exceed the intake capacity of the turbines. Review of data from a ten year period indicate this may be the case in perhaps two out of ten years.

Analyses were conducted relating April 1st snow water content to annual streamflow derived from the Boise River Drainage above Lucky Peak Dam. Estimates were made of the potential increases in streamflow that would result from a 12% increase in April 1st snow water content attributable to cloud seeding operations. A conservative estimate was then made regarding how much of this additional streamflow could be utilized in power production from Lucky Peak Dam. The average cost to produce this additional streamflow through cloud seeding was calculated to be $0.44 per acre foot. It was estimated that the average annual increase in power production would be $820,182. The resulting benefit/cost ratio would be 9.7/1. This analysis did not include any estimate of the value of the additional streamflow to downstream agricultural interests or from additional power generated at the Bureau of Reclamation's Anderson Ranch facility which is located above Lucky Peak Dam. Therefore, the 9.7/1 benefit/cost ratio is considered to be on the conservative side.

It is concluded that winter cloud seeding in the Boise River Drainage above Lucky Peak Dam is economically feasible.

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