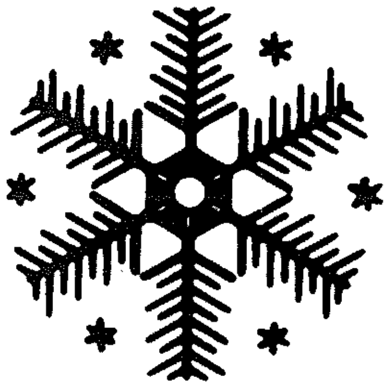
CONSUMPTIVE WATER USE IN ARTIFICIAL SNOWMAKING
SANTA FE SKI AREA, NEW MEXICO



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ABSTRACT

Field experiments were conducted at the Santa Fe Ski Area, New Mexico to determine the consumptive use of water in artificial snowmaking.

Evaporation losses during the snowmaking process were quantified by a mass balance approach and found to be 2.4% of the 14 acre-ft. of water diverted from a stream flowing underneath the snowpack. Sublimation and evaporation losses from the artificial snowpack were measured in the fall and spring using evaporation pans, and the results were weighted to yield seasonal totals. These snowpack losses were calculated to be 7.4% of the diversion, resulting in a total consumptive use of 9.8% of the diversion.

Sublimation and evaporation of the artificial snowpack in the spring accounted for most of the consumptive use (54%), evaporation from the snowmaking machine was 25%, and sublimation and evaporation in the fall was 21%.

INTRODUCTION

Ski areas in the western United States are becoming increasingly dependent upon artificial snowmaking to provide early season skiing opportunities when recreational skiing demand is highest. While amounts of water diverted for this use are often considerable, little is known about the consumptive losses. Quantification of these losses is of interest to watershed scientists, ski area managers, public resource officials, and other water users in affected watersheds.

There is currently no information available on the quantity of snow lost by evaporation and sublimation in artificial snowmaking for use in water rights determinations[1]. At the Santa Fe Ski Area, two mechanisms of consumptive use from artificial snowmaking were quantified in separate field experiments: 1) evaporation loss during snowmaking; and 2) sublimation and evaporation loss from an artificial snowpack. These experiments were conducted both in the fall, before artificial snow was covered with appreciable amounts of natural snow, and again in the spring, when artificial snow was uncovered and exposed to the atmosphere.

Although little information on evaporation loss from artificial snowpacks and from snowmaking machines is available, substantial work has been done to quantify natural snowpack sublimation and evaporation losses (Church 1912). Most of this work was done in the

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[1]Winter diversions for snowmaking would delay runoff of water not consumptively used and may benefit direct flow rights at the possible expense of downstream storage rights.

western United States and been used in the development of snowmelt and runoff prediction models. Sublimation and evaporation losses from Colorado, Utah and California mountains range from 0.011 to 0.067 in./day of water (Wilm and Connaughton 1943, Kittredge 1953, West 1959, Hutchison 1966, Doty and Johnston 1969, Anderson 1969).

Limited information on losses associated with snowmaking machines comes from a Swiss study which compared the relative capacities of 16 different machines to produce snow in an enclosed area (Bregenzer et al. 1980). However, the study did not measure water which drained through the snowpack, and study conditions were significantly different from those of normal operation. The results demonstrated that snow machines have varying degrees of efficiency in the conversion of water to ice crystals, and that temperature and humidity are important factors in the snowmaking process.

STUDY AREA

Studies were conducted at the Santa Fe Ski Area, located in the Santa Fe National Forest about 16 miles north of Santa Fe, New Mexico (Figure 1). Elevations at the area range from 10,350 ft. to 12,000 ft. and most snowmaking is done below the 11,000 ft. level. Average snowfall from November through April produces 9.27 in. of water, based on 11 years of observation (Tesuque Ranger District, Santa Fe National Forest, unpublished data). Night temperatures are cold enough for snowmaking by the middle of November.

Snowmaking is normally conducted on about 25 acres of ski trails from mid-November to mid-January at night, when temperatures are

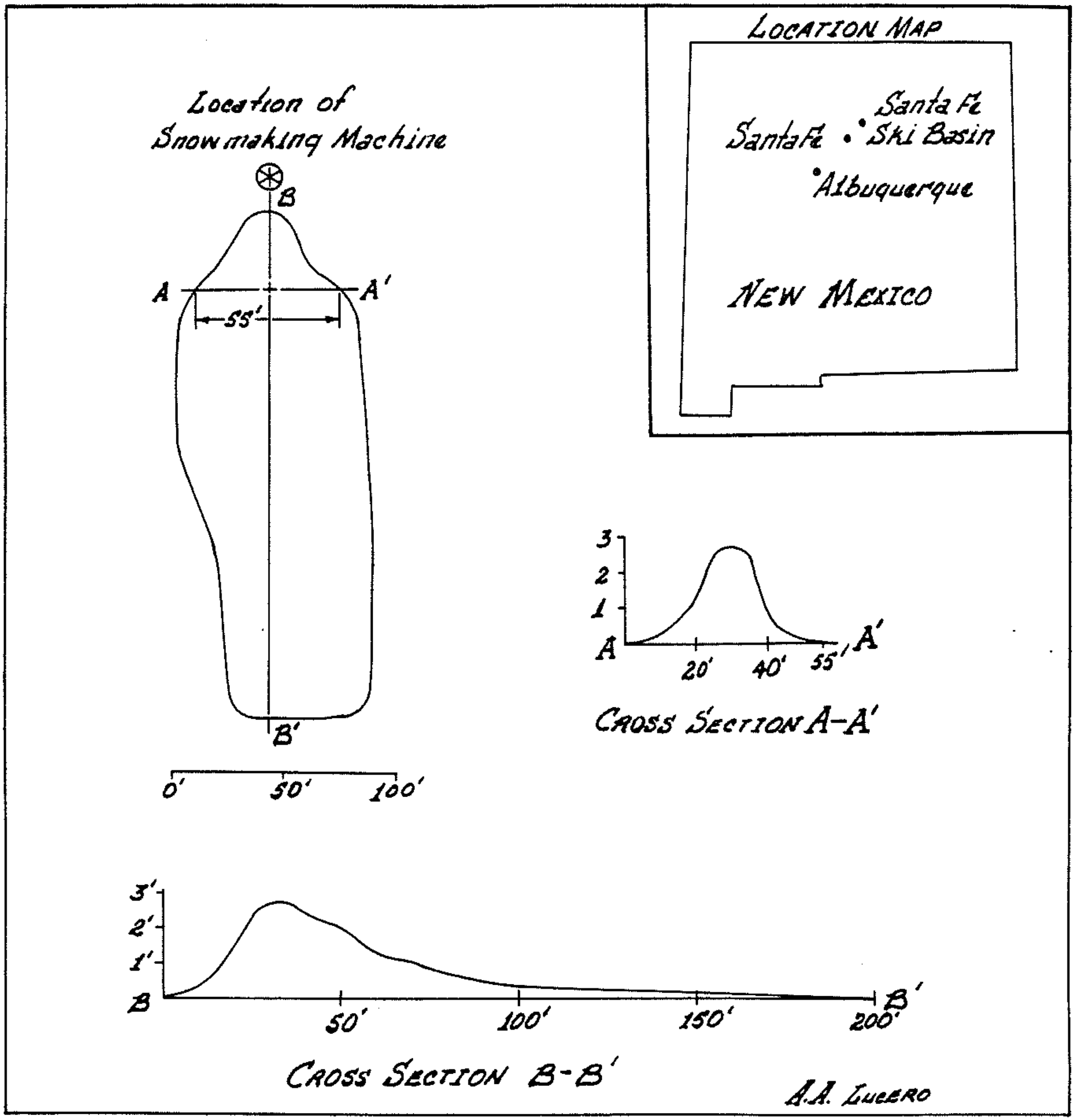

Figure 1. Location, shape and cross sections of artificial snow produced in experiments to measure the evaporative loss from a snowmaking machine.

coldest and winds relatively calm. The snowmaking experiment was conducted on a ski trail where artificial snow is normally made. The trail has a 5% slope with a west-northwest aspect at an elevation of 10,600 ft. The sublimation-evaporation station was located so that it would be representative of the aspect (west-northwest) and elevation (10,700 ft.) where artificial snow is made.

METHODS

Snow Machine Evaporation Losses

A mass balance approach was used to measure the evaporation loss from a Snowstream 320 snowmaking machine. Water input to the machine was metered, the water equivalent of snow produced was determined, and the difference between these amounts was assumed to be the evaporation loss.

Snow was captured on clear plastic sheeting placed over an area 200 ft. long and 80 ft. wide. Snow depths were measured in transects across the resulting artificial snowpack. Percent water equivalent was determined volumetrically at several depths and locations in the snowpack, and snow depths and areas were converted to volumes.

During the 4.5 hour experiment, carried out between 9 p.m. and 2 a.m. on January 11 and 12 of 1983, the air temperature averaged 18° F and the relative humidity was 48%. Wind speed averaged 6 mi./hr. with no strong gusts. The temperature, wind and night conditions are typical of those under which artificial snow is produced at the Santa Fe Ski Area.

Artificial Snowpack Sublimation-Evaporation Losses

Sublimation and evaporation losses from artificial snow were measured during the ablation period of 1982-83: from early April through early June of 1982 and from mid-November 1982 to mid-January 1983. A lucite evaporation container with a square surface area of 36 $in.^2$ and 6.1 in. high was filled with a block cut from the snowpack. It was placed so that the top of the block in the container was at snow level. The container and block were weighed and changed daily to determine sublimation loss or condensation gain. A drain tube in the bottom of the pan allowed melt water to drain into a separate chamber so that the water content of the block approximated that of the snowpack (Hutchison 1966).

Air temperature and humidity at the surface were monitored by a Belfort hygro-thermograph. The surface temperature of the snowpack and the wind speed were also measured. These measurements were not used for theoretical predictions because the equipment was not sophisticated enough to evaluate thermal and vapor pressure gradients. Changes in depth were measured daily until the end of the snowmelt period. During this time, natural snow was indistinguishable from artificial snow because of the ripening process. Fall measurements were made on artificial snow until a natural snow cover became significant.

RESULTS

Snow Machine Evaporation Losses

The artificial snowpack, produced in 4.5 hours, had the oblong shape indicated by Figure 1. Cross sections indicated that most of the snow was produced within 50 ft. of the machine. Depths ranged from a maximum of 2.71 ft. to less than .01 ft. at the edges of the study area.

Densities ranged from 44% water equivalent at the top of the profile to 57% at 12 in. and 81% at 33 in. Water not converted to ice crystals by the machine percolated through the snowpack during the experiment and froze or remained as capillary water near the base of the profile, thus increasing the density with depth. All of the snow and water from the machine remained on the plastic catchment.

Input to the machine was 1790 $ft.^3$ of water. The water equivalent of the snow produced was 1747 $ft.^3$, resulting in a loss of 43 $ft.^3$ (2.4% of the diversion).

Artificial Snowpack Sublimation-Evaporation Losses

Fall-Winter Period

Losses from the artificial snowpack occurred during the 79-day snowmaking period (November 10, 1982 to January 27, 1983). After January 27, natural accumulations covered the artificial snowpack, and it is assumed that significant losses did not occur until the spring period when artificial snow was again exposed to the atmosphere.

The measurement period (December 12 to January 12) includes only part of the snowmaking period. Therefore, the average loss rate for the measurement period (0.0034 in./day) is used to approximate the rate for the entire period. Losses for individual days are shown in Table 1.

Applying the average loss rate for the entire 79-day snowmaking period, the total sublimation-evaporation loss for the fall is 0.27 in. (0.022 ft.) water equivalent. The area on which losses occurred was approximately 12.8 acres, half of the total 25.6 acres. This average figure was used because none of the 25.6 acres on which snow was made had artificial snow at the beginning of snowmaking and all of the acreage was covered by the end of snowmaking. The loss amounted to 0.29 acre-ft. for 1982-83.

Spring Period

Thirty-five daily measurements of sublimation and evaporation were made from April 8 to the disappearance of the artificial snow on June 6. On days with precipitation accumulations or wind drift into pans, measurements were not recorded. Of the 35 daily periods, 32 periods had sublimation-evaporation losses, while 3 periods showed condensation gains (Table 1).

While the average daily loss for these 35 days was 0.036 in./day water equivalent, this snowmelt period includes the loss of both natural and artificial snow. To determine the appropriate period and rate for artificial snow, the average depth of artificial snow on the 25.6 acres was determined. Direct measurements of artificial snow depth were not considered accurate because of continuous movement by snow grooming machines and mixing with natural snow. The spring melt process further obscured any clear demarcation between natural

TABLE 1. EVAPORATION PAN MEASUREMENTS

(inches of water equivalent loss*)

Spring

Date		Loss
April	8	.032
	9	.034
	10	.027
	11	.028
	12	.061
	13	.061
	14	.026
	15	.034
	16	.023
	17	.037
	18	.040
	20	.037
	26	.034
	27	.007
	29	.041
	30	.013
May	2	- .022
	8	.005
	9	.029
	10	- .018
	11	.022
	15	.032
	17	- .010
	18	.024
	19	.054
	20	.076
	21	.047
	26	.017
	30	.050
	31	.056
June	1	.046
	2	.104
	3	.085
	4	.065
	5	.072

mean = .036 in./day

Fall - Winter

Date		Loss
Dec.	12	- .029
	13	.005
	14	- .011
	17	.035
	18	0
	19	- .030
	20	.017
	21	.006
	22	.020
Jan.	2	- .006
	3	.002
	4	.006
	5	.006
	6	.006
	7	.006
	9	- .024
	10	.033
	11	.031
	12	- .008

mean = .0034 in./day

* Negative values indicate condensation gains

and artificial snow. Therefore, an indirect method described below for determining average artificial snow depth was used.

The method involves determining the amount of water diverted for snowmaking and the calculation of the volume and depth of artificial snow remaining in the spring. Between November 10, 1981 and January 27, 1982, 14.03 acre-ft. of water were diverted for snowmaking (Santa Fe Ski Area unpublished data 1984). Deducting a 2.4% initial evaporation loss from the machine (0.34 acre-ft.) and a 0.29 acre-ft. loss during the fall period, the 14.03 acre-ft. of diversion reduces to 13.40 acre-ft. (water equivalent) of artificial snow remaining in the spring. Assuming an average artificial snow density of 0.54 g/cc (54% water equivalent as measured in the snowmaking experiment), the 13.40 acre-ft. of water is equivalent to 24.83 acre-ft. of snow. (Additional compaction of the artificial snow probably occurred during the winter and spring, but any changes in density were not measured.) This volume of snow covered the 25.6 acres to an average depth of 0.97 ft. (24.81 acre-ft./25.6 acres).

Next, the period in the spring when 0.97 ft. of artificial snow was lost through a combination of sublimation, evaporation and melt was defined. Observations in the artificial snowmaking area indicate that the last 0.97 ft. of snow disappeared during the period May 9 through May 30. This snow, at the base of the snowpack, was assumed to be artificial snow, as it was deposited on the ground before natural snow accumulated.

Data from sublimation-evaporation pans indicate that losses occurred on 10 days during this period and amounted to a total of

0.029 ft. of water. Therefore, the amount lost through sublimation-evaporation was 3% of the snowmelt for this time period (0.029/0.97). The average daily loss for 10 days was 0.034 in., which is within the reported 0.011-0.067 in./day range of sublimation and evaporation for natural snow (Wilm and Connaughton 1943, Kittredge 1953, West 1959, Hutchison 1966, Doty and Johnston 1969, Anderson 1969).

DISCUSSION AND CONCLUSIONS

For the 1981-82 snowmaking season, results can be summarized as follows:

0.29 acre-ft. lost by sublimation and evaporation in the fall

0.34 acre-ft. lost by evaporation from the snowmaking machine

.74 acre-ft. lost by sublimation and evaporation in the spring

1.37 acre-ft. lost by the artificial snowmaking process

The consumptive use was 9.8% of the initial diversion of 14.03 acre-ft. for snowmaking. Of these losses, sublimation and evaporation in the spring accounted for most of the loss (54%), evaporation from the machine was 25% of the loss, and sublimation and evaporation in the fall was 21%. On a per acre basis, the loss for the 25.6 acre area was 0.053 acre-ft./acre.

Evaporation losses from the soil surface or losses by transpiration of plants were not considered as consumptive losses of artificial snow. Evaporation from a wet soil surface occurs naturally after snowmelt. An artificial snowpack may delay the timing of an exposed soil surface to a time of higher evaporative demand, but this may be offset by a shortened evapotranspiration season due to a lengthened period of snow cover. Natural snows from November through April provide an average of 9.27 in. of water (U.S. Forest Service, 11 years of weather records at the ski area). Moisture storage available for plants for the Nambe soils at the ski area is estimated at 4.53 in. for a 52 in. soil depth from an area soil survey (Walker et. al. 1979). Soil moisture for the rooting zone is estimated to be 3.5 in. at the Rio en Medio soil moisture station maintained by the Soil Conservation Service near the ski area (Washichek and Moreland 1972). Therefore, natural snowmelt will completely recharge the plant-available moisture storage in an average year, and any artificial snowmelt will drain freely through the soil to recharge streamflow and ground water.

Some natural snow areas in clearings may lose snow cover before artificially covered areas due to a lower total snowpack. These areas may lose soil moisture through evaporation and low levels of transpiration before the exposure of some artificially covered areas occurs. Concerns that snowmelt from artificially snow-covered areas may recharge exposed areas and constitute a consumptive use of artificial snow were considered, but were determined not to be significant at this ski area for these reasons: 1) open areas at lower elevations in the drainage basin which might receive such recharge are ski runs on which artificial snow has been made, and 2) tree-covered areas have delayed natural snowmelt rates when compared to open areas, which extend the period of snow cover up to a month (Gary and Coltharp 1967). Exposure of the ground surface tree-covered areas occurs at about the same time as exposure of artificially snow-covered areas.

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