DESIGN OF A WATERSHED SNOW FENCE SYSTEM, AND FIRST-YEAR SNOW ACCUMULATION

By

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Introduction

Inducing snow accumulation with fences in areas with insufficient natural barriers can materially increase total snow storage by reducing sublimative "losses" and by diverting snow that would be transported further downwind. Snow fences provide a unique means of redistributing water on a drainage by concentrating snow in a relatively few large accumulations rather than in numerous smaller drifts. Snow can be stored at the best locations to improve either on-site use or water yield downstream. The reduced surface area/volume ratio potentially reduces evaporation losses and prolongs the melt period, and improves feasibility of subsequent management for evaporation reduction or melt rate regulation by means of surface additives.

The Study.-- This paper reports the first-year results from a snow fence system designed to test this form of snowpack management on a watershed basis. The approach used to design the treatment should be applicable in other locations.

The study area, located on Pole Mountain in southeastern Wyoming, has gently rolling topography, and lies between 8,000 and 8,500 feet elevation. Shortgrass vegetation predominates on the upland areas, with coniferous trees restricted to perennial water courses and some of the higher hills. Winters are characteristically cold, windy, and dry; seasonal snow accumulation typically begins in early November, and snowpack reaches a peak near the first of April. Winter thaws are short-lived, and snowmelt runoff during this period is uncommon. Because of the inevitable relocation of snowfall by wind, persistent snow cover in unforested areas is confined to topographic depressions and leeward of scattered trees and rocks.

Three watersheds, each about 100 acres, were instrumented in 1960-61 with stream gages, precipitation gages, and snow courses to determine the potential for artificially augmenting snow accumulation, and to assess the effects on seasonal and total runoff. The watersheds were calibrated until a snow fence was built on one of the drainages during the summer of 1969.

Designing The Snow Fence

Selecting the Treatment Watershed.-- One drainage was chosen to receive a snow fence treatment, leaving the other two (A and B) as controls. Selection of the 111-acre treatment watershed was based on experience as to availability of wind-blown snow, the opportunity to increase natural accumulation efficiently, and the nature of the hydrograph response to snowmelt.

Snow Accumulation before Building the Fence.-- Average annual peak snowpack water-equivalent was 0.63 area-inch during the 9 years of study before the fence was built. Estimated mean November 1 to April 1 precipitation over the same period was 5.9 inches; thus, snow storage on the test watershed averaged only about 11% of the winter precipitation, and 27% of the storage on control watershed A (Fig. 1), which has trees along the lower reach of channel to trap wind-blown snow.

An average of 84% of the total snowpack on the treatment watershed accumulated in a 1300-ft reach of draw that is approximately normal to the prevailing westerly winds. A representative cross-section of this channel (Fig. 2) shows that such a snow catchment could fill even in a relatively dry winter, and suggests a potential for increasing snow accumulation in this location.

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Location of the Fence.-- Soils derived from the underlying Sherman Granite are coarse and extremely permeable. High infiltration rates and a deep zone of fractured rock result in very little surface runoff from snowmelt in the absence of soil frost. By placing the fence so as to augment snow in the 1300 ft of channel in which most of the snow accumulated naturally, surface runoff could be maximized to reduce conveyance losses, while taking advantage of the topography to increase the capacity of the snow fence. Therefore, a single fence was planned to parallel this reach of channel at a distance of about five times the fence height upwind of the channel centerline, so that the deepest part of the drift would be contained within the channel. This decision fixed the fence length at 1300 ft, and required that the fence consist of two straight sections, angled as shown in Fig. 3. The northern leg is 620 ft long bearing N 10° E, and the southern leg is 680 ft long bearing N 32° E.

Amount of Snow Available to the Fence.-- The mean annual water-equivalent of snow available at the fence location, $\bar{Q}_T$, was assumed equal to the sum of relocated snow arriving at the fence, $\bar{Q}_b$, and precipitation falling directly on the lee drift ($\bar{Q}_p$); thus,

$$\bar{Q}_T = \bar{Q}_b + \bar{Q}_p \qquad (1)$$

On open sites, the proportion of snowfall swept away by the wind depends upon the abundance and capacity of vegetative and topographic traps for blowing snow, the amount of snow that melts or evaporates in place before being relocated, and the eroding and transporting ability of the wind relative to physical properties of the snow. The ratio of the amount of snow that is relocated to that which falls (precipitation) has been termed the snow transfer coefficient, θ (Komarov, 1954).

The amount of relocated snow (per unit width), q_b, arriving at a fence location, can be expressed as

$$q_b = \theta P R_c - q_L \qquad (2)$$

where P is the average precipitation received over the contributing distance R_c upwind. q_L is the total sublimation loss (per unit width) during transport over the distance R_c, and can be expressed as

$$q_L = \theta P \int_0^{R_c} S \, dr \qquad (3)$$

where S is the proportion of relocated precipitation that sublimates before reaching the fence. If we assume steady, uniform flow across a smooth horizontal surface of infinite extent (implying the absence of horizontal and temporal gradients for factors affecting sublimation), then the rate of sublimation should be constant with respect to time and travel distance. The amount of sublimation would be directly proportional to travel distance, R (Fig. 4). Thus,

$$S = R / R_m \quad , \quad R \leq R_m \qquad (4)$$

where the subscript m refers to the maximum distance snow can be transported before complete sublimation. By definition, the contributing distance, R_c , cannot exceed R_m. Substituting Eq. (4) into (3) and integrating gives

$$q_L = \tfrac{1}{2} \theta (P / R_m) R_c^2 \qquad (5)$$

For the winter, the mean transport loss for blowing snow (per unit width) over the mean contributing distance $\bar{R}_c$ would then be

$$\bar{q}_L \hat{=} \tfrac{1}{2} \bar{\theta} (P / \bar{R}_m) \bar{R}_c^2 \qquad (6)$$

Substituting Eq. (6) in (2) yields

$$\bar{q}_b \hat{=} \bar{\theta} P \bar{R}_c - \tfrac{1}{2} \bar{\theta} (P / \bar{R}_m) \bar{R}_c^2 \qquad (7)$$

$\bar{R}_c$ is the mean contributing distance averaged over all wind directions during the winter. For a specific wind direction, the sum of the contributing distances for each unit length of fence is equal to the contributing area, A_c. Substituting $\bar{A}_c$ to get the total available snow, Q_b , along the entire fence, we get

$$\overline{Q}_b = \overline{\theta}\ P\ \overline{A}_c - \tfrac{1}{2}\ \overline{\theta}\ P\ (\overline{R}_c\ /\ \overline{R}_m)\ \overline{A}_c \qquad (8)$$

Substituting this expression in Eq. (1) we get the mean annual water-equivalent of snow, $\overline{Q}_T$, available at a fence location:

$$\overline{Q}_T = \overline{\theta}\ \overline{P}\ \overline{A}_c - \tfrac{1}{2}\ \overline{\theta}\ \overline{P}\ (\overline{R}_c\ /\ \overline{R}_m)\ \overline{A}_c + \overline{P}\ A_f \qquad (9)$$

where A_f is the maximum surface area of the drift behind the fence.

Eq. (9) requires that R_c and R_m be known. Although more must be learned about the sublimation of blowing snow before these distances can be calculated with any certainty, reasonable estimates can suffice for useful approximations of Q_T.

For the location of the proposed fence, we assumed an equal probability of drifting winds between northwest and southwest. The average contributing distance was estimated to be 3650 ft (1.1 km), by methods described later. Russian investigators (Komarov, 1954) have reported maximum transport distances to range from 1 to 3 km. To estimate the amount of blowing snow available to the fence, we assumed that, in this case, the mean contributing distance ($\overline{R}_c$) was equal to the maximum transport distance ($\overline{R}_m$); thus, $A_m = A_c$. Eq. (9) then reduces to

$$\overline{Q}_T \cong \tfrac{1}{2}\ \overline{\theta}\ \overline{P}\ \overline{A}_c + \overline{P}\ A_f \qquad (10)$$

As an approximation for the snow transfer coefficient (θ), the value of 0.7 reported for western Siberia by Komarov (1954) was used. Long-term mean winter precipitation for the period November 1 to April 1 was estimated at 4.3 inches, from a correlation with a gage several miles from the study area. Barriers to snow movement upwind which were considered to have sufficient capacity to trap all incoming blowing snow, were identified in the field and located on aerial photographs to provide a source-area map (Fig. 5). The contributing area, A_c, was measured by planimeter for 5^o increments from north to south (through west), as shown for a N 45^o W wind in Fig. 5. Assuming that the wind direction associated with drifting events was equally probably from the northwest to the southwest, the mean contributing area was 84.5 acres. The lee drift surface area for the height of fence finally selected was 4. 2 acres, based on previous studies. Finally, the mean annual water-equivalent of snow available to the fence was estimated from Eq. (10) to be 12.1 ac-ft.

Height of the Fence.-- With the location and length of the fence dictated by topographic and hydrologic characteristics of the test watershed, the capacity of the fence system was largely a function of fence height. From another study, we have found fence efficiency to diminish at a decreasing rate as accumulation progresses. Therefore, to maintain a high trapping efficiency throughout the winter, a height was selected so that the fence would have a capacity about twice that of the estimated mean annual water-equivalent ($\overline{Q}_T$) available at the fence location. In a management situation, economic criteria would often determine the optimum height, much the same as has been proposed for determing the optimum spacing in a tandem series of fences (Tabler, 1968). Because the value of stored snow or resultant snowmelt runoff was unknown, height selection in this case was restricted only by the requirement that the choice be economically reasonable.

From a study on fence height we have derived an empirical expression for the equilibrium profile of a drift behind a vertical-slat fence of height H. The theoretical profiles for alternative fence heights were superimposed on cross-sections of the topography at representative points along the proposed fence location, from which the capacity of the various heights was estimated (Fig. 2). Heights considered were restricted to even multiples of the commercially available 4-ft vertical-slat fence material, with a 6-inch gap provided between the bottom of the fence and the ground to reduce the possibility of burying the fence in the drift. A 12½-ft height was chosen to give the required ($2\overline{Q}_T$) capacity. It was estimated that about 23.3 ac-ft of water (at a snow density of 0.40 g/cc) would be stored by such a fence when filled, or about 25% more than would be expected behind the same fence built on flat terrain. The fence capacity was thus about 190% of the estimated total snow available at the fence site.

Project Life and Fence Design. -- Standard woven wire and vertical-slat snow fencing was used because of the availability of material, reasonable cost, and because our earlier studies of fence height and spacing with this material made it possible to predict the fence performance. The supporting structure for the fencing material was designed for a physical life of about 25 years and a minimum of annual maintenance. This length of project life was thought to be necessary to amortize construction costs in a management situation, and 25 years is the expected life of the "penta"-treated poles used in the construction. Previous experience has shown the type of construction needed for this height of fence.

First-Year Results

Effects on Watershed Snowpack.-- Peak snowpack water-equivalent on the fenced watershed was increased about 70% (significant at the 0.99 level) based on the pretreatment correlation with the most sensitive control, drainage B (Fig. 1). Predicted snowpack water-equivalent was 1.0 area-inch, while the actual was 1.7 area-inches -- an increase of about 6.5 ac-ft. If the snow fence continues to maintain total snow storage about 7 ac-ft per year above "normal" over the 25-year project life, the value of the additional stored water-equivalent would have to be about $37 per ac-ft to amortize the initial $6500 construction cost.

Although certain sections of the lee drift were nearly at equilibrium by the end of the winter (April 1), other sections contained considerably less snow, so that the lee drift contained an average of 49% of the maximum accumulation expected if the fence were filled. Figures 2 and 6 compare snow accumulation before and after the fence was built.

Actual and Predicted Fence Performance.-- From Eq. (10), the amount of water, W, stored behind the snow fence over a period of time can be expressed as

$$W \cong \frac{1}{2} \bar{\theta} P \bar{E} \bar{A}_c + P A_f - G \qquad (11)$$

where E is the factor for fence trapping efficiency, and G is net evaporation and melt of the drift over the period.

To test the method used to determine the fence capacity, actual fence catch was compared with the estimate given by Eq. (11), for the period October 24 to April 6. It was assumed that $\bar{E} = 1.0$ and $\bar{\theta} = 0.7$ over this period. G was assumed to be 0 except for one 30-day interval during the winter which showed a net loss of 0.58 ac-ft in drift water content. This amount was added to the total accumulation during the period, and the estimated available water-equivalent for that period was not included.

The amount of snow available to the fence was estimated for each of the 20 drifting events that occurred during the period. Mean wind direction, and thus contributing area, was determined from a recording anemometer 400 ft upwind of the fence, and precipitation amounts were taken from a shielded recording gage located in a forest opening 2400 ft northwest of the center of the fence.

Total snow water-equivalent available at the fence was thus estimated to be 15.6 ac-ft; the fence caught about 72% (11.2 ac-ft) of this amount over the same period. Total precipitation was 6.7 inches. The difference between fence catch and estimated available snow can be attributed to a combination of factors. First, sublimation and melt losses from the drift during the period were undoubtedly larger than the loss measured over the one 30-day period. Second, even in the earliest stages of accumulation a snow fence is not completely effective in trapping all of the incoming wind-blown snow, and at present there is no satisfactory way of estimating fence efficiency. Third, the arbitrary choice of 0.7 for a snow transfer coefficient would not be representative for all events throughout the winter. Averaged over a period of years, θ might be expected to vary as shown in Fig. 7. Fourth, the average maximum transport distance, as defined in the simplified sublimation model, may in fact have been shorter than the assumed mean contributing distance (2786 ft) between the fence and the upwind barriers to snow movement. In support of this possibility, Komarov (1954) states that another Russian investigator has found 1 km (3281 ft) to be the *maximum* transport distance in the European part of the USSR.

Conclusions and Future Research

The procedures used to plan this snow fence treatment illustrate some of the factors that must be considered if efficient snow fence projects are to be designed. The

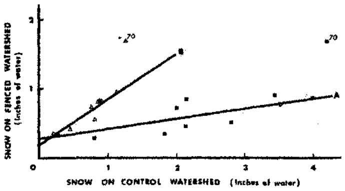

Figure 1. Pretreatment relationships for peak snowpack water-equivalent, comparing the fenced watershed and the two control drainages (A and B). Solid symbols are shown for the first year (1970) after the fence was built.

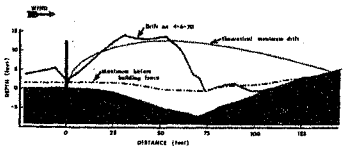

Figure 2. The maximum snow accumulation at Transect 2 during the 9 years of pretreatment observations, compared with the snow profile after building the fence. Snow storage in 1970 was about 65% of the maximum accumulation expected when the fence is filled.

Figure 3. Aerial view of the watershed snow fence on February 5, 1970. Prevailing westerly winds are from the lower left corner of the photograph. Note the reduced snow cover downwind of the fence.

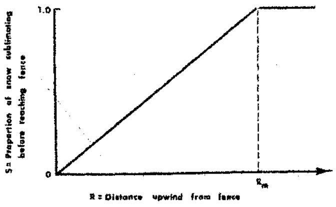

Figure 4. Simplified model for sublimation loss, S of wind-blown snow as a function of distance R upwind of a fence. R_m is the maximum distance snow can be transported before complete sublimation, under a given set of meteorological conditions.

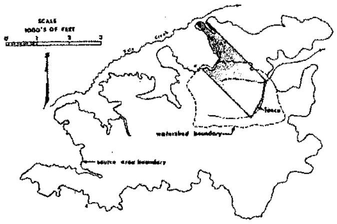

Figure 5. Map of the source area for wind-blown snow on the fenced watershed. The shaded region contributes snow to the fence with a N 45° W wind.

Figure 6A. Appearance of the snow cover at the fence location before the fence was built, 3-31-69.

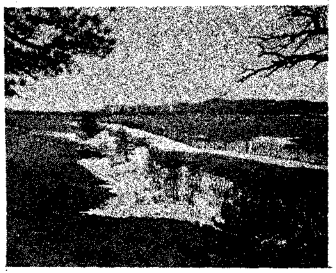

Figure 6B. Appearance of the snow cover at the fence location after the fence was built, 2-26-70.

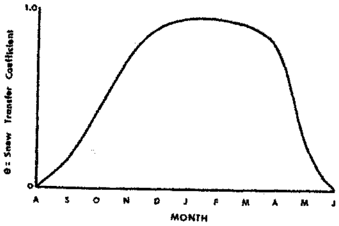

Figure 7. Hypothetical variation of the snow transfer coefficient with time (at the study area), if averaged over a period of years.

estimate of the amount of relocated snow available at our test site agreed reasonably with that caught behind the fence during the first winter, and the method should be useful in the design of snow fence projects elsewhere. Evaluation of this approach will continue over the next few years.

The assumptions and approximations that had to be used to plan this fence system, particularly those required to estimate snow transport distances, snow transfer coefficients, and fence trapping efficiency, show the need for more knowledge about blowing snow and its sublimation, and suggest promising areas for future research.

First-year results show that fences can significantly increase the snowpack on small watersheds, and demonstrate the potential for snow management in windswept areas. Several more years of study will determine if there are commensurate effects on total and seasonal runoff, and on characteristics of the snowmelt hydrograph.

LITERATURE CITED

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APPENDIX - NOTATION

The following symbols are used in this paper:

Q_T = Total annual water-equivalent of snow available at a fence site.

Q_b = Amount of relocated snow available at a fence location.

Q_p = Amount of precipitation falling directly on the lee drift.

q_b = Amount of relocated snow arriving at a fence location, per unit width.

q_L = Total sublimation loss, per unit width, during transport over the distance $\underline{R}$.

θ = Snow transfer coefficient (defined as the ratio of the amount of snow that is relocated to that which falls as precipitation).

P = Precipitation.

R_c = Contributing distance (distance upwind contributing snow to a fence).

S = Proportion of relocated precipitation sublimating before reaching the fence.

R_m = Maximum distance snow can be transported before complete sublimation.

A_c = Contributing area (area contributing snow to a fence).

A_f = Maximum surface area of the drift behind a fence.

W = Water-equivalent of snow stored behind a fence.

E = Fence trapping efficiency coefficient.

G = Total evaporation and melt of a drift.